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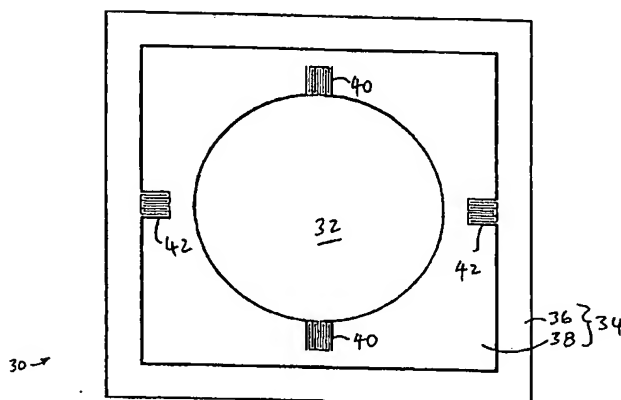
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(54) Title: **ELECTROSTATICALLY ACTUATED MICRO-ELECTRO-MECHANICAL DEVICES AND METHOD OF MANUFACTURE**



(57) Abstract: One embodiment is directed to a gimbal mechanism for a MEMS mirror device having folded flexure hinges (40, 42). Another embodiment is directed to a gimbal mechanism having a frame with through-holes or recesses (72) distributed thereabout to reduce weight of said frame. Other embodiments are directed to improved electrode structures for electrostatically actuated MEMS devices. Other embodiments are directed to methods for fabricating electrodes electrostatically actuated MEMS devices. Other embodiments are directed to methods of fabricating through-wafer interconnect devices. Other embodiments are directed MEMS mirror array packaging. Other embodiments are directed to electrostatically actuated MEMS devices having driver circuits integrated therewith. Other embodiments are directed to methods of patterning wafers with a plurality of through-holes. Other embodiments are directed to methods of forming moveable structures in MEMS devices. Other embodiments are directed to methods of depositing a thin film on the back of MEMS device.



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ELECTROSTATICALLY ACTUATED MICRO-ELECTRO-MECHANICAL DEVICES AND METHOD OF MANUFACTURE

Related Application

The present application is based on and claims priority from U.S.
5 Provisional Patent Application Serial No. 60/276, 814 filed on March 16, 2001
and entitled Electrostatically Actuated Micro-Electro-Mechanical Device and
Method of Manufacture.

Background of the Invention

Field of the Invention

10 The present invention relates generally to micro-electro-mechanical
(MEMS) devices and, in particular, to arrayed electrostatically actuated
MEMS devices such as, e.g., arrayed mirrors used in optical switches.

Description of Related Art

One example of the use of arrayed electrostatically actuated MEMS
15 devices is in an optical switch. FIGURE 1 schematically illustrates an example
of an optical cross-connect 12 of an optical switch. The cross-connect 12
includes an array of collimators or other beam-forming devices (represented
by grid 14), which forms incoming optical communications signals into beams
that impinge on an array of moveable reflectors or mirrors represented by
20 grid 16. Each beam from grid 14 has its own corresponding moveable mirror
on grid 16.

The moveable mirrors of grid 16 are controllably positioned so as to
individually direct the respective beams from grid 14 to respective moveable
mirrors of a second array of moveable mirrors, represented by grid 18. The

moveable mirrors of grid 18 are positioned so as to individually direct the beams received from grid 16 to respective beam receivers of an array of beam receivers represented by grid 20. The beam receivers may take various forms, such as transducers, or optical elements for coupling the respective beams
5 into respective waveguides, or the like. As with grids 14 and 16, each moveable mirror of grid 18 is associated with a particular beam receiver of grid 20, so that each receiver receives beams on a single axis. The arrow 20 shows a representative signal path from grid 14 to grid 20.

The movable mirrors can be steered or controllably tilted about one or
10 more axes. Mirror movement can be actuated in a variety of ways including through electro-magnetic actuation, electrostatic actuation, piezoelectric actuation, stepper motors, thermal bimorph and comb-drive actuation.

In electrostatically actuated mirror arrays, each mirror in the array is movably mounted on a base structure having a set of steering electrodes. The
15 steering electrodes can be selectively actuated to generate electrostatic forces to tilt the mirror to a desired position.

Attempts have been made to fabricate arrays of movable mirror using MEMS technology, in which silicon processing and related techniques common to the semiconductor industry are used to form micro-electro-
20 mechanical devices.

Brief Summary of the Invention

The present invention is directed to improved electrostatically actuated MEMS devices and methods of manufacturing such devices. The various embodiments of the invention include the following.

5 One embodiment of the invention is directed to a gimbal mechanism for a MEMS mirror device having folded flexure hinges. Another embodiment of the invention is directed to a gimbal mechanism having a frame with through-holes or recesses distributed thereabout to reduce weight of said frame. Other embodiments of the invention are directed to improved
10 electrode structures for electrostatically actuated MEMS devices. Other embodiments of the invention are directed to methods for fabricating electrodes for electrostatically actuated MEMS devices. Other embodiments of the invention are directed to methods of fabricating through-wafer interconnect devices. Other embodiments of the invention are directed to
15 MEMS mirror array packaging. Other embodiments of the invention are directed to electrostatically actuated MEMS devices having driver circuits integrated therewith. Other embodiments of the invention are directed to methods of patterning wafers with a plurality of through-holes. Other embodiments of the invention are directed to methods of forming moveable
20 structures in MEMS devices. Other embodiments of the invention are directed to methods of depositing a thin film on the back of a MEMS device.

These and other features of the present invention will become readily apparent from the following detailed description wherein embodiments of the invention are shown and described by way of illustration of the best mode of
25 the invention. As will be realized, the invention is capable of other and

different embodiments and its several details may be capable of modifications in various respects, all without departing from the invention. Accordingly, the drawings and description are to be regarded as illustrative in nature and not in a restrictive or limiting sense with the scope of the application being

5 indicated in the claims.

Brief Description of the Drawings

For a fuller understanding of the nature and objects of the present invention, reference should be made to the following detailed description taken in connection with the accompanying drawings wherein:

5 FIGURE 1 is a schematic illustration of an example of an optical cross-connect;

FIGURE 2 is a plan view schematic diagram of a mirror pixel device in accordance with one embodiment of the invention;

10 FIGURE 3 is an enlarged plan view of a single spring of the mirror pixel device shown in FIGURE 2;

FIGURES 4A and 4B are schematic plan and cross-sectional views, respectively, of a flexure hinge in accordance with one embodiment of the invention;

15 FIGURE 5A and 5B are perspective views of flexure hinges in accordance with other embodiments of the invention;

FIGURE 6 is a schematic plan view of an inner gimbal frame in accordance with another embodiment of the invention;

20 FIGURES 7A and 7B are schematic cross-sectional and plan views, respectively of an electrode structure in accordance with one embodiment of the invention;

FIGURES 8A-8C are plan views of portions of electrode structures and gimbal frames in accordance with other embodiments of the invention;

FIGURES 9-11 are schematic cross-sectional views of electrode structures in accordance with further embodiments of the invention;

5 FIGURES 12A and 12B are cross-sectional and plan views, respectively illustrating a bump-stop in accordance with another embodiment of the invention;

10 FIGURES 13A-13M are cross-sectional schematic views illustrating the fabrication of a glass wafer interconnect device and shaped electrodes in accordance with another embodiment of the invention;

FIGURES 14A and 14B are cross-sectional schematic views of holes powder blasted from two sides of a wafer used in the fabrication of a glass wafer interconnect device;

15 FIGURES 15A-15E are cross-sectional schematic views illustrating the process for patterning a wafer with through holes using a "tenting" approach in accordance with one embodiment of the invention;

20 FIGURES 16A-16F are cross-sectional schematic views illustrating the process for patterning a wafer with through holes using through-wafer electroplating, lapping and polishing in accordance with another embodiment of the invention;

FIGURES 17A-17D are cross-sectional schematic views illustrating the

process for creating silicon bridges using heavy boron doping of silicon to span through holes to enable conventional photolithographic processing in accordance with another embodiment of the invention;

FIGURES 18A-18C are cross-sectional schematic views illustrating the
5 process for creating silicon bridges to span through holes using SOI wafers to enable conventional photolithographic processing in accordance with another embodiment of the invention;

FIGURES 19A-19M are cross-sectional schematic views illustrating the
process for creating suspended mirror structures over separately processed
10 electrode structures in accordance with another embodiment of the invention;

FIGURES 20A-20F are cross-sectional schematic views illustrating the
process for creating a shadow mask for deposition of gold on the back of
mirrors for stress compensation in accordance with another embodiment of
the invention.

FIGURE 21 is a cross-sectional schematic view of a MEMS array
15 illustrating the integration of driver circuits in accordance with another embodiment of the invention;

FIGURE 23 is a cross-sectional schematic view of an angled window
bonded to a MEMS array chip in accordance with another embodiment of the
20 invention;

FIGURES 23A-23C are perspective, exploded and cross-sectional views,
respectively, of a mirror array package in accordance with one embodiment of

the invention; and

FIGURE 24 is a cross-sectional view of a MEMS mirror array package in accordance with another embodiment of the invention.

Detailed Description of Preferred Embodiments

The present invention is generally directed to improved electrostatically actuated MEMS devices and methods of manufacturing such devices. These MEMS devices can have a range of applications including, e.g., use in optical switches, relays, optical scanners, optical displays, laser writing systems, and laser printers.

Mirror Support Structure

A first embodiment of the invention is directed to an improved structure for movably supporting mirrors in a mirror array. FIGURE 2 illustrates a single electrostatically actuated mirror device or pixel 30. The pixel 30 forms part of a mirrored array comprising a plurality of such pixels. The mirror device 30 includes a mirror 32 movably supported on a gimbal structure 34 in a "mirror-in-frame" configuration. The gimbal structure 34 includes an outer frame 36 and an inner frame 38. The outer frame is connected to the inner frame by a pair of opposed flexure hinges 42 defining a first axis of rotation for the mirror. The outer frame is fixed relative to a base structure on which the gimbal structure is supported. The inner frame 38 is connected to the mirror 32 by a second pair of opposed flexure hinges 40 defining a second axis of rotation, which is preferably perpendicular to the first axis. Electrodes (not shown in FIGURE 2) positioned below the mirror-in-frame structure can be selectively actuated to generate electrostatic forces to cause attraction and tilting of the mirror 32 about the axes.

A variety of different types of flexure hinges can be used in the gimbal structure. FIGURE 3 is an enlarged view of one of the flexure hinges 40, 42 shown in FIGURE 2. As shown, the flexure hinges 40, 42 have springs 44 with multiple folds, which allow the pitch of the mirrors to be lowered and their

maximum deflection angle be increased. (Mirror pitch refers to the spacing between mirror centers of adjacent pixels in a mirror array.). The springs 44 increase torsional compliance of the hinges while reducing out-of-plane compliance. The springs 40, 42 also take up less space in their longest dimension (which is in a radial direction from the mirror center) than conventional straight springs and thereby help to reduce the overall pixel area. FIGURE 3 shows an example of a spring with 7 folds. It should be realized, however, that other folded spring designs that have a greater or lesser number of folds and occupy different areas are also possible. The particular design used may be chosen based, e.g., on performance criteria, ease of fabrication, and other considerations.

The flexure hinges 42 are connected to the frame 38, which has most of its mass positioned further from the mirror center than the mirror, which is connected to flexure hinges 40. It is therefore often desirable to have the flexure hinges 42 be stiffer than the flexure hinges 40 in order to have better control of the part with greater moment of inertia. Furthermore, the frame 38 can often be arranged to have a larger torque to reach its maximum angle than the mirror and can therefore tolerate a stiffer spring. Therefore, if desired, the flexure hinges 42 can be different from the flexure hinges 40, with the torsional compliance of the hinges 42 being lower than that of the hinges 40. In some situations it may be desired to have the flexure hinges 42 have a higher torsional compliance than those of the flexure hinges 40.

Other flexure hinge designs can also be used including, e.g., those with a non-uniform cross-sectional configuration. For example, an alternative flexure hinge having a folded cross-sectional configuration is shown in FIGURES 4A and 4B. FIGURE 4A is a top view of the flexure hinge connecting the mirror 32 to the inner gimbal frame 38. FIGURE 4B is a cross-

sectional view of the flexure hinge taken along lines 4B-4B of FIGURE 4A.

The flexure hinge is a spring with a generally U-shaped configuration. Such a spring can provide a larger ratio of out-of-plane stiffness to torsional stiffness than is possible with a spring having a uniform cross-section. The cross-
5 sectional and top view dimensions of the hinge can be varied to optimize various performance and space requirements.

Other flexure hinges with different cross-sectional shapes are also possible including, e.g., V-shaped springs. In addition, each flexure hinge can
10 include multiple U or V or other cross-sectional members.

FIGURES 5A and 5B illustrate further alternative flexure hinges 60, 62. The flexure hinges 60, 62 have both a folded top view spring arrangement as well as a folded cross-sectional configuration. The FIGURE 5B flexure hinge
15 62 is elongated and generally has greater torsional compliance than the FIGURE 5A flexure hinge 60. Accordingly, if the two flexure hinges 60, 62 are used in the same gimbal mechanism, the FIGURE 5B hinge 62 can be used for connecting the mirror 32 to the inner gimbal frame 38, and the FIGURE 5A hinge 60 can be used for connecting the inner gimbal frame 38 to the outer
20 gimbal frame 36.

The gimbal structure of the mirror-in-a-frame design of the pixel 30 shown in FIGURE 2 allows simultaneous movement of the mirror 32 about two perpendicular axes. Accordingly, generally all combinations of mirror
25 rotation can be realized, subject to maximum mirror tilt restrictions. Circular or elliptical mirrors are preferred over square mirrors because circular or elliptical mirrors allow for the placement of electrodes beneath the mirror to be closer to the mirror. This is because, for rotation about a diagonal of a square, a square mirror will have a long lever arm along its diagonal and the

electrode must be placed sufficiently far below the mirror to allow for a large swing of the arm. Circular or elliptical mirrors have a smaller maximum lever arm for a given area, and the minimum mirror-electrode distance (along the axis normal to the mirror) requirements are therefore relaxed. By placing the electrodes closer to the mirror, many benefits can be achieved, including increased torque on the mirror at a given voltage. Also, the ratio of an elliptical mirror's major and minor axes can be chosen so that the mirror appears circular to the incident light (often coming in at an angle with respect to the axis normal to the mirror).

10

Furthermore, the inner and outer gimbal frames 36, 38 can be configured to obtain the appropriate trade-off between moment of inertia and torque to meet the performance requirements of a given system. For example, the gimbal frames can have an outer square shape with mirror cutout (as shown, e.g., in FIGURE 2), or alternatively, a concentric or elliptical shell around the mirror. The particular shape of the gimbal structure can be selected based on desired performance requirements.

15

Hollowed out gimbal frame embodiment

20

As shown in FIGURE 6, in accordance with another embodiment of the invention, a movable inner frame 70 of a gimbal structure can include a plurality of etched holes 72. The holes 72 can be recessed or thinned out areas or, alternatively, through-holes. The holes reduce the weight of the frame and give the frame a lower moment of inertia.

25

Holes in a variety of shapes and arrangements can be provided. Preferably, the gimbal structure includes through-holes in a honeycomb lattice like configuration, which makes the frame particularly light weight, but structurally sound.

The choice of whether through-holes or recesses (or some combination thereof) are used depends on a number of factors including whether or not, and to what extent, control of air damping of the system is desired.

5

Electrode Structure

Further embodiments of the invention are directed to improved electrodes for actuating mirror motion, and methods for fabricating such electrodes. As previously discussed, electrostatically actuated MEMS mirror devices include electrodes positioned beneath movable mirrors. The electrodes can be selectively charged to generate electrostatic forces to attract and tilt the mirror about a given axis. Generally, two electrodes are provided for each axis of rotation. Other arrangements are also possible. For example, it is possible to use a total of three electrodes for the two axes of rotation.

Prior art electrodes are generally flat and plate-like. They are positioned parallel to the movable mirror with a uniform spacing between the electrode and the movable mirror. Two common problems with such an electrode structure are (1) only a relatively small torque can be generated at small angular displacements of the mirror, and (2) the non-linearity of that torque. The prior art electrodes are positioned sufficiently far from the original (untilted) position of the movable mirror to allow the mirror to move through a wide range of motion. This relatively large distance between the mirror and the electrodes limits the initial electrostatic force that can be applied to the mirror, resulting in lower applied torque, particularly at small angular deflections. Accordingly, high actuation voltages are needed, and the switching speeds are slow.

25

Furthermore, the shapes of the deflection versus voltage-squared curves of these electrodes are very non-linear, which greatly increases the difficulty of controlling the device externally. This also leads to the "pull-in" phenomenon, which results in instability when the mirror moves to within a certain distance from its original untilted position from a tilted position. Typically, the travel range of mirror is limited to between 30 to 50% of the original gap, which is the distance between the edge of the mirror in an untilted position and the electrode.

Previous attempts to linearize the deflection versus voltage-squared curves, avoid the pull-in phenomenon, and increase torque generally have been made using comb-drive actuation mechanisms. Such mechanisms generally suffer from problems of fabrication complexity and relatively low production yields.

Electrodes in accordance with various embodiments of the invention generally include the advantages of comb-drive actuation mechanisms, while maintaining the ease-of-fabrication and high yield aspects of conventional electrostatic plate actuation mechanisms.

FIGURE 7A is a simplified cross-sectional view of a mirror device 100 having an electrode structure 102 in accordance with one embodiment of the invention. FIGURE 7B is a top view of the electrode structure 102 (with the mirror 32 indicated by a dashed line). For simplicity, only one axis of rotation 104 for the mirror 32 is illustrated. It should be understood, however, that multiple axes of rotation are possible with electrode structures in accordance with the various embodiments of the invention. In the FIGURE 7 embodiment, two electrodes are provided. Each electrode includes an inner portion 106 generally beneath the mirror 32, and an outer portion 108 near the

rim of the mirror. The inner portion of each electrode is stepped with an inner raised portion 110 underneath the mirror 32 nearer to the mirror center. The inner raised portions 110 of the electrodes provide additional torque without significantly limiting the range of motion of the movable mirror 32.

5

While each electrode is shown having joined inner and outer portions, it should be understood that the inner and outer portions can be separate electrodes that can be independently actuated.

10 The outer portions 108 of the electrodes are raised and positioned outside of the path or sweep of the mirror 32 so as not to restrict mirror movement. The outer electrodes 108 generate electrostatic forces that provide a relatively large initial torque to the mirror 32. The outer electrodes 108 act on the outer portion (i.e., rim) of the mirror, where there is the longest lever arm. Low voltages can accordingly be used to cause large mirror
15 displacements. The outer electrodes 108 also help to linearize the voltage versus angular deflection curve for the movable mirror by providing "pull back" on the mirror 32 as the outer edge of the mirror 32 rotates past the top edge of the outer electrodes 108. This helps to linearize the voltage versus
20 angular deflection curve for the movable mirrors.

Because the outer portions 108 of the electrodes are located relatively far from the rotation axis 104 of the mirror, the ratio of the torque to the downward force generated by these electrodes is high. This suppresses the
25 undesired so-called "piston" mode mirror movement, in which the entire mirror moves up and down rather than rotates about the axis.

Furthermore, for a curved rotator, different parts of the rotator pass the top of the secondary electrode at different angles. Accordingly, the shape can be chosen to provide an even more optimized angle vs. voltage curve.

5 The outer portions 108 of the electrodes can have various configurations relative to the inner movable gimbal frame of the gimbal structure supporting the mirror. This can affect the torque generated and torque versus angle curves. A few examples of different shapes of the outer electrodes 108 and the adjacent portion of gimbals are shown in top view in
10 FIGURES 8A-8C. FIGURE 8A illustrates a generally straight outer electrode (108')-gimbal (38') arrangement. FIGURE 8B illustrates a piecewise curved electrode (108'')-gimbal (38'') arrangement. FIGURE 8C illustrates a comb-fingers like arrangement of the electrode 108''' and gimbal 38'''. The particular configuration selected can be based on a number of different criteria such as
15 e.g., desired torque, moment of inertia, alignment accuracy for bonding the mirror-gimbal structure to the raised electrode structure, and lateral vibration expected.

 The inner portions 106 of the electrodes can have various geometric
20 shapes. For example, in accordance with another embodiment of the invention, the inner portion 106' of each electrode has a multiple stepped geometry (as shown, e.g., in FIGURE 9. Providing the additional steps enable the torque-vs.-angle behavior of the system to be more accurately tailored.

25 An inner electrode structure 106'' in accordance with another embodiment has a gradually sloped configuration is shown in FIGURE 10.

 An inner electrode structure 106''' in accordance with another embodiment includes only outer electrodes as shown in FIGURE 11.

In accordance with a further embodiment of the invention as shown in FIGURES 12A and 12B, a bump-stop 120 is provided to restrain the mirror 32 from over-rotating and possibly shorting with the electrodes, which may be uncovered. The bump-stop 120 can be formed, e.g., by depositing oxide
5 between the left and right electrodes underneath the mirror. The bump stop can have an annular configuration as shown in FIGURE 8B, which illustrates the top view of the bump stop.

10 The above described electrode structures can also generally be used in a parallel plate actuator that is designed to move a mirror up and down in a piston-like motion rather than rotate.

Electrode Fabrication

15 Raised electrode structures in accordance with various embodiments of the invention can be fabricated using the process described in the example below with reference to FIGURES 13A-13M. The initial steps in the process relate to forming a through-wafer interconnect device for supporting and providing electrical connections to mirror pixel devices.

20

(1) Provide a starting glass wafer 200 (e.g., Pyrex 7740) as shown in FIGURE 13A. This wafer will form the through-wafer interconnect device on which the electrode structure can be supported. Other insulating materials such as, e.g., quartz, alumina, ceramic, etc. can also be used to form the interconnect
25 device. Silicon can also be used if insulated, e.g., with a growth of thermal oxide thereon.

(2) Deposit a seed layer 202 (e.g., Ti/Cu) on one or both sides of the wafer 200 depending on whether a subsequent powder blasting step is to be performed on one or both sides of the wafer. For ease of illustration, the process being described illustrates powder blasting from only one side of the wafer.

5 FIGURE 13A accordingly shows a seed layer 202 deposited on only the front side of the wafer 200.

(3) Pattern thick photoresist 204 as mold for copper plating on the seed layer 202 of the wafer 200 as shown in FIGURE 13C. (If powder blasting is to be
10 performed on both sides of the wafer, pattern the photoresist on both sides.)

(4) Electroplate copper 206 in the photoresist mold and strip the photoresist as shown in FIGURE 13D. The copper can be annealed at this point to change material properties as required for given electroplating/blasting conditions.

15 The copper is used as a mask for subsequent powder blasting. Other materials can also be used such as, e.g., polymer films.

(5) Use powder blasting or AJM (Automatic Jet Machining) to drill very small holes 208 through the Pyrex wafer 200 using the copper mold as a mask as
20 shown in FIGURE 13E. (If powder blasting is to be performed from both sides, front to backside alignment should be performed.) These holes may also be formed using other methods such as, e.g., ultrasonic drilling, and laser ablation. At this point, after stripping the masking material, the wafer can be annealed to relieve any stress induced during the formation of the holes.

25

(6) Pattern metal 210, e.g., Ti/Au, using dry resist as shown in FIGURE 13F. This can be done, e.g., either using lift-off or by wet etching. At this stage, it is possible to attach the wafer to a carrier wafer and use conventional photoresist or polyimide "tenting" for patterning especially small features.

(7) On a separate, preferably low resistivity, double-side polished silicon wafer 220 grow a thick oxide 222 (about 1.5 μm) and strip off the backside as shown in FIGURE 13G. The thickness of the wafer can, e.g., be 250 μm .

5

(8) Pattern and etch the backside to a depth of about 50 μm with DRIE as shown in FIGURE 13H.

(9) Remove the oxide 222 in areas that will form the inner lower electrodes as shown in FIGURE 13I.

10

(10) Bond the silicon and Pyrex wafers 220, 200 as shown in FIGURE 13J.

Also, pattern the backside of the glass wafer with metal 224, e.g., Ti/Au, using any of a number of methods including dry-resist, conventional

15 photoresist, polyimide or tenting.

(11) Deposit masking material 226, e.g., Al, on the topside of the silicon wafer and pattern as shown in FIGURE 13K.

20 (12) Etch grooves or trenches 228 down to a depth of about 100 μm as shown in FIGURE 13L.

(13) Strip Al and continue etching to the desired depth for the lower electrodes, punching through to the areas 230 etched from the back during the etch as shown in FIGURE 13M. A bump stop could be formed from the masking oxide on the top a central member 232 forming a grounded electrical shield between two electrodes.

25

Fabrication of Through-Wafer Interconnects

Another embodiment of the invention is directed to providing electrical connections to a large number of pixel devices using a through-wafer interconnect device. This device allows for the transfer of the electrical leads from the electrodes for driving each mirror to external contacts directly through a wafer on which the mirrored array is supported. These leads can then be connected to external circuitry using, e.g., area array technology. This embodiment of the invention is generally directed to a device for electrically connecting devices on one surface from leads on another surface. Devices in accordance with this embodiment provide such interconnects while allowing only relatively small parasitic capacitances both on the through-wafer part of the connection routing and in any additional routing on either side of the wafer.

15

A fabrication process in accordance with this embodiment of the invention involves fabricating structures that contain through-wafer electrical interconnects. This process generally involves making holes through a preferably glass wafer (e.g., a Pyrex wafer), and either completely or partially filling these holes with a conducting material, and then patterning the conducting material on one or both sides of this wafer. The use of an insulating material for this wafer helps facilitate a reduction in unwanted parasitic capacitances in the system.

25

There are a number of different processing techniques for fabricating structures with through wafer interconnects. The preferred method as described below involves fabricating the holes by using powder blasting or AJM. This process allows the fabrication of through holes in Pyrex, which is otherwise difficult to machine with small holes that are placed close together.

Furthermore the process is more economical and has higher throughput than serial techniques (such as laser ablation). Pyrex is a widely used material that can be anodically bonded to silicon and is also TCE (Thermal Coefficient of Expansion) matched to silicon. Other aspects of the process that relate to
5 patterning material in and around the holes are not dependent on the particular process used to make the holes.

The general process for fabricating the through-holes with powder blasting is as shown in FIGURES 13A-13E described above. Various
10 parameters are chosen for the given structure of the holes being blasted and the desired profile, including, e.g., masking material and method of implementation, size and nature of particles used for blasting, and blasting parameters (size of nozzle, angle of nozzle, pressure, etc.). Also, small through-holes can be made in thicker wafers than otherwise possible by
15 blasting the wafer from both sides using front to backside alignment. This commonly creates a through-hole 240 with an hourglass type profile as shown, e.g., in FIGURE 14A. Also the mask openings can be chosen differently on different sides to give better control of each side's openings as also shown, e.g., in the through-hole 242 of FIGURE 14B.

20

Once the through holes have been formed in the wafer, a number of techniques can be used to pattern conductive material on both sides of the wafer. One approach is to electroplate up plugs through the wafer from a base and then lap and polish both sides of the wafer in order to make each
25 side suitable for subsequent processing (photolithography, electroplating, etc.). If the holes are large and or close together, then a soft metal is preferable over a hard one in order to allow for elevated temperature post-processing without causing cracking from TCE mismatch induced stress on the wafer. These holes can then serve to electrically connect the topside of the Pyrex

wafer to the backside. The fabrication process for these conducting vias is outlined below and described in connection with FIGURES 16A-16F below.

If the holes are not plugged, there are several ways to pattern material on either side of the wafer. One way to pattern metal is to spin thick photoresist on the wafer and then bake out very slowly. This can be particularly effective if minimum feature sizes are not too small and if a carrier wafer or a non-vacuum chuck is used. Also, so called dry-resist can be used for patterning of large features ($>15\text{ }\mu\text{m}$). This known process includes applying photoresist as a sheet that is laminated onto the wafer.

However, if very small features are to be reliably patterned, a different approach can be used. One possible approach involves the use of polyimide. When polyimide is spun on the wafer it forms membranes over the holes. If the baking out of the solvents is done slowly enough, the membranes can remain intact through a full cure. The wafer then has much smaller topography and conventional photoresist can be spun on the wafer, allowing for patterning of smaller features. The polyimide can be removed after patterning the underlying material, making the technique applicable to those processes involving polyimide as well as those that do not. Other similar materials with similar properties could be used instead of polyimide such as, e.g., BCB (benzo-cyclob-butene). This process can be applied to a wafer of any type with holes fashioned in generally any way.

This process is described in greater detail below with reference to FIGURES 15A-15E. Note the process shown is just one example of the use of the tenting process. It can also be used with lift-off, and if the carrier wafer remains attached, the process can leave the metal or other material to be patterned within the holes. The particular embodiment is described below:

- (1) Provide a Pyrex wafer 250 with holes, e.g., by using the process described above in FIGURES 13A-13E. Evaporate or sputter Ti/Au 252 on the Pyrex wafer as shown in FIGURE 15A. If evaporation is used, the wafer can
5 be placed at an angle with respect to the line of sight between the evaporation source and the wafer. The evaporation can be carried out with a rotatable substrate holder.
- (2) Attach the wafer 250 to a carrier wafer 254 (or alternately apply
10 material such as cello tape to the back of the wafer) and spin polyimide 256 on the wafer and softbake slowly as shown in FIGURE 15B.
- (3) Remove carrier wafer 254 (or cello tape) and cure polyimide as shown
15 in FIGURE 15C.
- (4) Deposit Al 258 on top side and pattern and etch, and then use as hard
mask for oxygen plasma etch of polyimide as shown in FIGURE 15D.
- (5) Attach cello tape to back of the wafer and etch Ti/Au. Remove
20 cello tape and strip resist (if any remains after oxygen plasma), Al and polyimide as shown in FIGURE 15E.

To obtain full metal coverage along the sidewall of the holes a number of methods are available including, but not limited to: sputtering from one or
25 both sides, high-angle evaporation with rotation from one or both sides, either of the above followed by either electroless plating or electroplating, CVD (Chemical Vapor Deposition) deposition of metal.

A process to fill the holes with conducting plugs is described, e.g., in FIGURES 16A-16F. This process is as follows:

- (1) Spin resist on a pre-oxidized silicon wafer 270, hardbake, and deposit
5 Ti/Au 272 as a seed layer for the subsequent electroplating as shown in FIGURE 16A.
- (2) Spin resist on top of the seed layer, attach the Pyrex wafer 274 (formed, e.g., as previously described in FIGURES 13A-13E) to the wafer 270, and then
10 bake as shown in FIGURE 16B.
- (3) Place wafer stack in oxygen plasma and remove resist from the bottoms of the holes as shown in FIGURE 16C.
- 15 (4) Electroplate metal 276 (e.g., gold) up through the holes as shown in FIGURE 16D.
- (5) Lap and polish wafer from topside as shown in FIGURE 16E.
- 20 (6) Remove carrier wafer and lap and polish the backside if desired as shown in FIGURE 16F.

At this point, the wafer is ready for conventional lithography on both sides and has conducting plugs electrically connecting the two sides together.

25

In accordance with another embodiment, an additional process is used to provide a smoother surface for subsequent lithography as shown in FIGURES 17A-17D. This process involves the use of a known boron etch-stop method.

- (1) Grow native oxide 292 on silicon wafer 290, strip off backside and pattern on topside as shown in FIGURE 17A.
- 5 (2) Implant the topside of the wafer 290 with large dose of P-type dopant 294 (e.g., boron), strip the oxide 292, and anneal as shown in FIGURE 17B. The parameters chosen for the implantation and the subsequent anneal generally determine the thickness of this layer.
- 10 (3) Anodically bond this silicon wafer to the glass wafer 296 with holes (formed, e.g., as previously described in FIGURES 13A-13E), aligning the heavily doped layers to the through-hole openings as shown in FIGURE 17C.
- (4) Dissolve the silicon wafer in EDP (ethylene diamine pyrocathecol),
15 leaving silicon membranes 294 over the holes as shown in FIGURE 17D. These membranes are very conductive as a result of their heavy implantation. This side is now suitable for subsequent patterning.

In accordance with another embodiment, a similar structure can be
20 formed using an SOI (silicon on insulator) wafer instead of a selectively doped silicon wafer. This process is illustrated in FIGURES 18A-18C.

- (1) Bond an SOI wafer 310 (device side down) to the glass wafer 312 with holes (formed, e.g., as previously described in FIGURES 13A-13E) as shown in
25 FIGURE 18A. The device layer 314 is preferably heavily doped if it is to serve as an electrical lead transfer at the end of the process.
- (2) Protect the backside of the wafer stack with any material that can withstand chosen wet etch (e.g., Au), and strip away handle wafer and oxide

on top side as shown in FIGURE 18B. At this point, the protecting material can be stripped if desired.

- (3) Pattern and etch silicon on topside leaving silicon membranes 314 over
5 through holes as shown in FIGURE 18C.

Fabrication of MEMS Mirror Arrays

A further embodiment of the invention is directed to a process for
10 making preferably large arrays of mirrors. The process includes a dry-release method process in which polyimide fixes the devices that will eventually be released. The polyimide does not have to completely cover these devices, but can be patterned to fix the devices at their edges. This makes it possible to fabricate an optically smooth and clean surface that is not covered with
15 polyimide, but is nonetheless held in place by it.

The process also allows for the fabrication of flexures in the gimbal structure from polysilicon. This is advantageous because a reliable and uniform polysilicon deposition can be provided, which controls the thickness
20 of the flexures. The spring constants of the flexures can therefore be tightly controlled. This allows for very accurate control of the flexures' torsional spring constants. An additional step in the process enables the polysilicon to be removed from the single crystal silicon that forms the mirror so as to avoid any warping of the mirror from this film.

25

An example process flow for the general fabrication of the mirror arrays is described below with reference to FIGURES 19A-19M. The process flow describes major processing steps for first the silicon wafer, and then the silicon and glass wafer stack after the two wafers have been bonded.

(1) Start with an SOI wafer 320 with oxide indicated at 321 as shown in FIGURE 19A.

5 (2) Oxidize the wafer 320 as indicated by 323 (with a thickness of about 1 μm) shown in FIGURE 19B.

(3) Pattern oxide 322 on the topside of the wafer 320 as shown in FIGURE 19C.

10

(4) Etch silicon to the BOX (Buried Oxide Layer) oxide in select areas 324 as shown in FIGURE 19D.

(5) Deposit a thin layer of polysilicon 326 as shown in FIGURE 19E. Also,
15 remove oxide from the backside of the wafer. Implant with the same ion type (n or p type) as the original starting silicon wafer. The same type is preferably used in order to avoid the formation of a diode in the bulk silicon. Anneal the silicon wafer to relieve the stress of the polysilicon. The final released devices (both the springs, the frame, and the mirror) comprise polysilicon,
20 and this step inhibits any warping of the structures, which could degrade mechanical performance and mirror flatness.

(6) Pattern and etch springs with the BOX oxide as an etch stop at 328 as shown in FIGURE 19F. These springs are etched within the thinned area and
25 are generally the thickness of the deposited polysilicon film. The polysilicon on top of the mirror is also etched away in this step using the oxide from step (2) as an etch stop.

- (7) Spin and cure a polymer (e.g., polyimide) 330 on the topside of the wafer as shown in FIGURE 19G. Deposit aluminum 332, which is then used as a hard mask for an O₂ etch of the underlying polymer. Any material that can be etched and that is not attacked vigorously in O₂ plasma can be used in this step. The polyimide is removed in the area where the gold will be patterned for the mirror. Strip oxide from mirror surface.
- (8) Deposit a reflective metal 334 (e.g., Au) and etch away in certain areas leaving mirrors as shown in FIGURE 19H. It is also preferable to deposit on top of the final reflective material a sacrificial material (e.g., Ti) that can be removed at the end of the process and protects the underlying material throughout.
- (9) On the topside of the wafer spin thick protective resist 336 and Al 338 as shown in FIGURE 19I. On the backside of the wafer pattern thick resist and etch silicon all the way to the front side oxide.
- (10) Strip Al, photoresist, BOX oxide, and protective material (e.g., Ti) as shown in FIGURE 19J.
- (11) Deposit epoxy bumps 340 via screen-printing on selected areas of the backside of the silicon wafer as shown in FIGURE 19K.
- (12) Bond this silicon wafer 342 to the already-processed glass wafer (e.g., from FIGURE 13F) as shown in FIGURE 19L. This bonding can be done with a flip-chip machine. At this step, a pre-formed covering window (not shown) can be bonded.

(13) Release mirrors 334 by etching the polymer 330 on the topside of the wafer as shown in FIGURE 19M preferably using a dry etch such as a gas plasma etch.

5 This fabrication process allows production of mirror arrays having a reduced mirror pitch. Conventional wet etching (KOH, TMAH or other type) can be used to define the space between the mirrors and the electrodes. However, this places large constraints on the minimum anchor size between the edge of one mirror and the edge of the next. This is because wet etching
10 generally creates holes that become smaller as they are etched. Thus, in order to separate mirrors on one side of the wafer, the holes must be significantly larger on the other side of the wafer. In the preferred process, this wet etch is replaced with a DRIE (Deep Reactive Ion Etch) etch, which allows the mirrors to be placed much closer together, while still providing complete electrical
15 isolation from pixel to pixel. However, the use of wet etching may still be possible depending on the etchant and the requirements for the size and spacing of the mirrors.

 The polysilicon on top of the single crystal silicon forming the mirror
20 support is stripped away if desired to further minimize the stress on the mirrors.

 The coverage of the mirrors with a sacrificial layer until the end of the process is useful to keep this surface shiny and undamaged.

25

 In accordance with another embodiment, a shadow masking technique can be utilized to apply gold to the backs of the mirrors. This technique is useful not only to minimize the radius of curvature ("ROC") of the mirror but

also the change in this ROC with temperature. This process is illustrated in FIGURES 20A-20F as described below.

- 5 (1) Start with a double side polished silicon wafer 360 whose thickness is chosen based on the thickness of the SOI wafer used to make the mirrors as shown in FIGURE 20A.
- 10 (2) Grow thermal oxide 362 (about 1.5 μm thick) and strip off of the top side as shown in FIGURE 20B. Deposit Al 364 on the top side of the wafer, pattern and etch it.
- (3) Pattern the oxide 362 on the back of the wafer 360 with thick resist 366 and leave the resist on to aid in the etch mask for the DRIE from the back as shown in FIGURE 20C.
- 15 (4) Etch topside of the wafer 360 to a pre-determined depth that is chosen based on design of the electrodes and the starting SOI wafer thickness as shown in FIGURE 20D.
- 20 (5) Etch through the wafer 360 from the back to the Al etch stop 364 as shown in FIGURE 20E. Strip the resist, aluminum and oxide.
- (6) Affix the wafer 360 (tape, resist, etc.) to the device wafer 368 and evaporate Ti/Au from the back 370 with the same parameters as it was
25 deposited from the front as shown in FIGURE 20F.

The springs can be made of single crystal silicon either by starting with SOI wafers and thinning back, or by performing a selective epitaxial growth of silicon. This is advantageous as single crystal silicon has certain

advantages over polycrystalline silicon (polysilicon) in terms of its mechanical properties.

5 The use of a sacrificial polymer 330 allows for safe release of the delicate structures without damage and also stabilizes the delicate silicon wafer during processing.

10 In accordance with another embodiment, a method of fabricating a MEMS mirror-gimbal structure is provided. The method includes (1) providing a silicon-on-insulator wafer having a device layer and a handle layer; (2) patterning the device layer to form flexure hinges of a gimbal mechanism; (3) performing selective epitaxial growth of silicon on the device layer to form a thickened silicon layer; and (4) patterning the thickened silicon layer to form a mirror and a gimbal frame of the gimbal mechanism.

15

Mirror Device Controllers

20 In accordance with another embodiment of the invention, individual mirror pixel devices in a mirror array are controlled using driver circuits such as ASIC (Application Specific Integrated Circuit) controllers. The ASIC controllers enable real time control of mirrors and allow the monitoring and precise adjusting of mirror positions. In particular, the controllers are able to control mirrors in the unstable pull-in phase of mirror movement. The dynamic range of each mirror can be increased, and the use of lower voltages to drive the mirrors is possible.

25

As shown in FIGURE 21, ASIC controllers 400 can be attached directly to the backside of a MEMS mirror array 402 using, e.g., flip-chip bonding on a glass wafer 404 supporting the mirror pixels. Other IC packaging and die-

attachment methods are also possible including, e.g., wire bonding and/or tape-automated-bonding (TAB). The signals from the ASICs are re-routed through the wafer to bond pads that can be connected by various methods (e.g., bump bonding) to external circuitry.

5

A single ASIC controller can be used to control a plurality of mirror pixels. The use of the ASICs along with time-multiplexing and/or serial-digital input methods results in fewer connections to mirror packages (e.g., less than 100) as compared to the typical connection number of one
10 connection per electrode (which can be, e.g., greater than 5000 for a mirror array).

Mirror Array Packaging

In accordance with another embodiment of the invention, a pre-
15 formed, angled glass (preferably Pyrex) or other transparent material window 420 is used to hermetically seal the topside of a MEMS mirror array 422 as shown in FIGURE 22. This window 420 can be anodically bonded to the interconnect wafer on which the mirror array is supported. An angled window is preferred over a flat window to avoid light reflected from the
20 windows surface to interfere with other beams of light.

Another embodiment of the invention is directed to the packaging and assembly of a large MEMS mirror array including the ASICs attached to the backside of the MEMS array as shown, e.g., in FIGURES 23A-23C and 24.
25 FIGURES 23A-23C illustrate perspective, exploded and cross-sectional views, respectively, of a mirror array package 450. After the attachment of the ASICs, a MEMS mirror array is assembled into a package body. The package body provides environmental protection, heat dissipation, and electrical connection to the MEMS mirror array. As shown in FIGURE 24, which shows

another example of a MEMS package 460, the package body can also include passive electronic components 462. The package body includes a substrate or base 464 with a cavity 466, a seal ring 468, and conductors to provide electrical interconnection. The package body can be manufactured from various
5 materials including ceramic, metal or some combination thereof. The body can comprise a flat metal base with a ceramic substrate laminated on top of it. The ceramic substrate can be a multi-layer structure that provides very high-density circuitry and can incorporate passive electronic components. In the preferred embodiment, the cavity 466 in the package body exposes the metal
10 base. The metal base is a high thermal conductivity material with a coefficient of thermal expansion (CTE) matching the CTE of the ceramic.

The seal ring 468 can be made of a metal alloy providing a close CTE match to the ceramic. The seal ring can be brazed to the package body,
15 surrounding the cavity 466. To provide shielding from electromagnetic interference (EMI) for the MEMS, the seal ring 468 can be electrically connected to a conductive and grounded plane underneath the cavity at several points. In the preferred package body, the metal base can serve as this conductive plane. To assemble the MEMS array to the package body, the
20 MEMS array 470 is centered over the cavity 466, with the ASICs 472 on the back of the MEMS array pointed towards the cavity. The MEMS die is affixed to the package body along the edge of the cavity and electrical connection between the MEMS array and the package body is achieved by flip chip bonding, wire bonding or tape automated bonding, or a combination of these
25 technologies. The gap between the back of the ASICs 472 and the bottom of the cavity is filled with a thermal conductor to create a path of low thermal resistance between the ASICs and the ambient air through the package body. This thermal path removes heat dissipated by the ASICs and, thus, controls the temperature of the ASIC's active surface.

A lid 474 is provided to hermetically seal the MEMS mirror array from the environment. The lid can be metal with a glass window 476 hermetically sealed to it. The glass window 476 can be sealed to the lid 474, e.g., brazing, soldering, or glass frit bonding. The lid 474 can be bonded to the seal ring 468 on the package body to form the hermetically sealed cavity. The bonding of the lid to the seal ring 468 is preferably done by seam welding, but could also be achieved by laser welding, brazing, or soldering. A near hermetic seal could be achieved by using an adhesive with very low moisture permeability and a bond line design optimized for low moisture penetration.

To minimize loss in the intensity of the light passing through the window 476, both surfaces of the window are preferably covered with an anti-reflection coating optimized for one or multiple wavelength ranges used in the application.

To avoid the build-up of electrostatic charges on the window surface, the lid surface can be covered with a transparent, electrically conductive layer. Such a layer can be made of, among other materials, indium tin oxide (ITO). The thickness of this layer can be optimized to provide adequate electrical conductivity, while at the same time, not creating excessive optical loss. For the conductive layer to perform its function, it needs electrical connection to the metal lid. This electrical connection can be achieved by, e.g., using a conductive solder, braze, or glass frit to seal the window to the lid, an electrically conductive material dispensed between the glass and the lid after the sealing, or by conformal deposition of the conductive layer over the lid and the window after the sealing process. Once the lid is sealed to the seal frame and electrical connection between the seal frame and the lid is established, a Faraday cage is formed around the MEMS device, ASICs, and passive electronics components by the lid, the electrically conductive layer on

the window, the seal ring, the conductive plane under the cavity, and the electrical connections between the seal ring and the conductive plane as shown in FIGURE 24. This Faraday cage will protect the MEMS mirror array from electrostatic and electromagnetic interference.

5

To avoid optical interference between the light beams steered by the mirrors and light reflected from either surface of the window, the thickness and the distance between the window and the mirror surface can be optimized. Such optical interference occurs if light bouncing off from a mirror that is parallel to the window is reflected by the window and falls back onto another mirror that is also parallel to the window. The thickness of the window and the distance between the window and the MEMS mirror can be chosen in such a way that light bouncing off from a mirror that is parallel to the window is reflected by the window will not fall onto another mirror.

10

15 Another way to avoid such interference is by angling the window in such a way that it will not be parallel to any mirror at any time.

Having described various preferred embodiments of the present invention, it should be apparent that modifications can be made without departing from the spirit and scope of the invention.

20

Claims

1. A MEMS mirror device, comprising:

a mirror;

5 a gimbal structure for movably supporting the mirror, the gimbal structure including two pairs of flexure hinges, each pair defining an axis about which said mirror can be rotated, at least some of said flexure hinges having a folded configuration in a cross-section taken generally perpendicular to a respective axis to increase torsional compliance about said respective axis and to decrease compliance in other directions; and

10 a mechanism for actuating the mirror.

2. The MEMS mirror device of Claim 1 wherein each flexure hinge has a generally U-shaped cross-sectional configuration.

3. The MEMS mirror device of Claim 1 wherein each flexure hinge has a generally V-shaped cross-sectional configuration.

15 4. The MEMS mirror device of Claim 1 wherein each flexure hinge has multiple folds.

5. The MEMS mirror device of Claim 1 wherein said pairs of flexure hinges comprise an inner pair connecting the mirror to an inner gimbal frame, and an outer pair connecting the inner gimbal frame to an outer gimbal frame, and wherein said outer pair have lower torsional compliance compared to the inner pair.

20

6. The MEMS mirror device of Claim 1 wherein each flexure hinge comprises a plurality of springs, and wherein said springs are arranged in a folded configuration in a top view thereof.

7. A MEMS mirror device, comprising:

5 a mirror;

a gimbal structure for movably supporting the mirror, the gimbal structure including two pairs of flexure hinges, each pair defining an axis about which said mirror can be rotated, said flexure hinges each comprising multiple springs in a folded configuration, each spring also
10 having a folded configuration in a cross-section taken generally perpendicular to a respective axis to increase torsional compliance about said respective axis and to decrease torsional compliance in other directions; and

a mechanism for actuating the mirror.

8. The MEMS mirror device of Claim 7 wherein each spring has a
15 generally U-shaped cross-sectional configuration.

9. The MEMS mirror device of Claim 7 wherein each spring has a generally V-shaped cross-sectional configuration.

10. The MEMS mirror device of Claim 7 wherein each spring has multiple folds.

20 11. The MEMS mirror device of Claim 7 wherein said pairs of

flexure hinges comprise an inner pair connecting the mirror to an inner gimbal frame, and an outer pair connecting the inner gimbal frame to an outer gimbal frame, and wherein said outer pair have lower torsional compliance compared to the inner pair.

5 12. A MEMS mirror device, comprising:

 a mirror;

 a support structure for movably supporting the mirror, the support structure including a movable portion with a plurality of holes distributed about said movable portion to reduce weight thereof and provide
10 a lower moment of inertia; and

 a mechanism for actuating the mirror.

 13. The MEMS mirror device of Claim 12, wherein said holes are through-holes to affect air damping of the device.

 14. The MEMS mirror device of Claim 12, wherein said holes are
15 recesses extending only partly through said movable portion of said support structure.

 15. The MEMS mirror device of Claim 12, wherein said holes are thinned out areas etched in the structure.

 16. The MEMS mirror device of Claim 12 wherein said support
20 structure is a gimbal mechanism.

17. The MEMS mirror device of Claim 16, wherein said gimbal mechanism comprises an inner and outer frames, and wherein said movable portion comprises said inner frame.

18. The MEMS mirror device of Claim 12, wherein said holes are
5 arranged in a honeycomb lattice-like configuration.

19. The MEMS mirror device of Claim 12, wherein said mechanism comprises at least one electrode for electrostatically actuating said mirror.

20. A MEMS mirror device, comprising:

a mirror;

10 a support structure for movably supporting the mirror, said mirror being movable along a given path; and

at least one electrode for electrostatically actuating the mirror, said at least one electrode having at least a portion thereof positioned about the periphery of said mirror and outside of said path.

15 21. The MEMS mirror device of Claim 20 wherein said at least one electrode includes an inner portion positioned beneath said mirror.

22. The MEMS mirror device of Claim 21 wherein said inner portion includes a raised portion.

23. The MEMS mirror device of Claim 21 wherein said inner portion

is sloped.

24. The MEMS mirror device of Claim 21 wherein said inner portion is stepped.

25. The MEMS mirror device of Claim 20 wherein said at least one
5 electrode comprises a side electrode and has one end proximate the edge of the mirror when said mirror is in an unactuated position.

26. The MEMS mirror device of Claim 20 wherein said support structure includes a movable portion, and wherein said at least one electrode and said movable portion are arranged in close alignment.

10 27. The MEMS mirror device of Claim 26 wherein said at least one electrode and said movable portion have a corresponding comb-fingers arrangement.

28. The MEMS mirror device of Claim 20 wherein said support structure comprises a gimbal mechanism for rotating said mirror about two
15 axes, and wherein said at least one electrode comprises two pairs of electrodes, each pair for actuating said mirror about one of said axes.

29. The MEMS mirror device of Claim 20 further comprising a bump stop to restrict movement of said mirror beyond a given position.

30. A MEMS mirror device, comprising:

20 a mirror;

a gimbal structure for rotatably supporting the mirror, said mirror being movable along a given path; and

two pairs of electrodes for electrostatically actuating the mirror about said axes, each electrode having at least a portion thereof positioned
5 about the periphery of said mirror and outside of said path.

31. The MEMS mirror device of Claim 30 wherein each electrode includes an inner portion positioned beneath said mirror.

32. The MEMS mirror device of Claim 31 wherein said inner portion includes a raised portion.

10 33. The MEMS mirror device of Claim 31 wherein said inner portion is sloped.

34. The MEMS mirror device of Claim 31 wherein said inner portion is stepped.

15 35. The MEMS mirror device of Claim 30 wherein each electrode has one end proximate an edge of the mirror when said mirror is in an unactuated position.

36. The MEMS mirror device of Claim 30 wherein said gimbal structure includes a movable inner frame, and wherein one pair of said electrodes and said movable inner frame are arranged in close alignment.

20 37. The MEMS mirror device of Claim 36 wherein said one pair of

electrodes and said movable inner frame have a corresponding comb-fingers arrangement.

38. The MEMS mirror device of Claim 30 further comprising a bump stop to restrict movement of said mirror beyond a given position.

5 39. The MEMS mirror device of Claim 38 wherein said bump stop is located between said electrodes.

40. A method of fabricating electrodes for an electrostatically actuated MEMS device, comprising:

providing a wafer;

10 forming recesses on a first side of said wafer for defining one end of each electrode;

affixing said first side of said wafer to a support substrate;

forming grooves on a second side of said wafer opposite said first side to define an opposite end of said electrodes; and

15 extending said grooves on said second side to reach said recesses on said first side to define said electrodes.

41. The method of Claim 40 wherein said wafer comprises a silicon wafer.

42. The method of Claim 40 wherein said support substrate comprises a device that provides for electrical interconnection from one side of a wafer to the other.

43. The method of Claim 42 wherein said interconnect device
5 comprises a through-wafer interconnect device having a plurality of through-holes, and wherein said electrodes are each positioned over a through-hole.

44. The method of Claim 40 wherein forming grooves and recesses comprises etching said grooves and recesses.

10 45. The method of Claim 40 wherein forming grooves on a second side of said wafer comprises selectively etching said second side using an oxide layer as a mask, and wherein said oxide layer forms a bump stop.

46. A method of fabricating a through-wafer interconnect device for use with a MEMS device, comprising:

15 providing a glass wafer;

forming holes through the wafer using powder blasting; and

filling or lining the holes with an electrically conductive material.

47. The method of Claim 46 wherein the glass wafer comprises a
20 Pyrex wafer.

48. The method of Claim 46 wherein forming the holes comprises powder blasting the holes on opposite sides of said wafer.

49. The method of Claim 48 wherein said holes have an hour-glass like configuration to more securely hold conductive plugs.

5 50. A method of fabricating a through-wafer interconnect device for use with a MEMS device, comprising:

forming holes through a wafer;

electroplating conductive material through said holes; and

lapping both sides of the wafer to prepare wafer surfaces for
10 subsequent photolithography processes.

51. The method of Claim 50 further comprising attaching the wafer to a carrier wafer prior to the step of electroplating, and removing the carrier wafer from the wafer prior to lapping a side of said wafer to which said carrier wafer is attached.

15 52. The method of Claim 50 wherein said wafer comprises a glass wafer.

53. The method of Claim 50 wherein said wafer comprises a Pyrex wafer.

54. A method of fabricating a through-wafer interconnect device for

a MEMS device, comprising:

selectively implanting a side of a silicon wafer with P-type dopant comprising Boron;

5 bonding the side of the silicon wafer to a wafer having a plurality of holes therethrough, said holes being aligned with doped portions of said silicon wafer; and

dissolving the silicon wafer, leaving silicon membranes extending over said holes.

10 55. An electrostatically actuated MEMS mirror array apparatus, comprising:

an array of electrostatically actuated MEMS mirror devices; and

an angled transparent window bonded to said array for passage therethrough of optical signals.

15 56. The apparatus of Claim 55 wherein said transparent window comprises a glass window.

57. The apparatus of Claim 55 wherein said transparent window comprises a Pyrex window.

58. The apparatus of Claim 55 wherein said window is bonded to interconnect wafer on which said array of electrostatically actuated MEMS

mirror devices is supported.

59. A MEMS mirror array package, comprising:

a base;

a MEMS mirror array device on said base;

5 a lid including a window, said lid covering said base and said MEMS mirror array device; and

a seal ring between said lid and said base.

60. The package of Claim 59 wherein the MEMS mirror array device includes a MEMS mirror array and one or more ASIC controllers attached
10 thereto.

61. The package of Claim 60 further comprising a thermally conductive material between said ASIC controllers and said base for heat dissipation.

62. The package of Claim 59 further comprising passive electronic
15 components in said package.

63. The package of Claim 59 wherein the base comprises a metal base with a ceramic substrate laminated thereon.

64. The package of Claim 63 wherein the coefficient of thermal

expansion of the metal base generally matches that of the ceramic substrate.

65. The package of Claim 59 wherein said seal ring comprises metal alloy.

66. The package of Claim 65 wherein the seal ring has a coefficient
5 of thermal expansion generally matching that of the base and lid.

67. The package of Claim 66 wherein the seal ring is electrically connected to a conductive and grounded plane formed by the base.

68. The package of Claim 59 wherein said lid is hermetically sealed to said base.

10 69. The package of Claim 59 wherein said window of the lid surface is covered with a transparent, electrically conductive layer.

70. The package of Claim 69 wherein said conductive layer comprises indium tin oxide.

15 71. The package of Claim 69 wherein said lid comprises metal and said conductive layer is electrically connected to the lid.

72. The package of Claim 71 wherein said conductive layer is electrically connected to the lid using an electrically conductive material disposed between the window and the lid.

73. The package of Claim 59 wherein a Faraday cage is formed

around the MEMS mirror array device to protect the MEMS mirror array device from electrostatic and electromagnetic interference.

74. An electrostatically actuated MEMS mirror array apparatus, comprising:

5 an array of electrostatically actuated MEMS mirror devices; and

a plurality of driver circuits integrated in said mirror array apparatus, each driver circuit associated with one or more of said mirror devices to control movement of respective mirrors.

75. The apparatus of Claim 74 wherein said driver circuits comprise
10 ASIC (Application Specific Integrated Circuit) controllers.

76. The apparatus of Claim 74 wherein said driver circuits are attached to a back-side of the array.

77. The apparatus of Claim 76 wherein each driver circuit controls a plurality of mirror devices using time-division multiplexing.

15 78. The apparatus of Claim 76 wherein each driver circuit controls a plurality of mirror devices using serial digital input.

79. The MEMS mirror device of Claim 30 wherein said gimbal structure includes a frame surrounding said mirror, and wherein said frame is curved or angled to provide a range of lever arms during frame movement
20 in order to obtain desired force versus displacement characteristics.

80. A method of patterning a wafer having a plurality of through-holes, comprising:

spinning a material on said wafer;

slowly baking said wafer so that said material forms a membrane over
5 each of said through-holes; and

patterning the wafer.

81. The method of Claim 80 wherein said material comprises polyimide.

82. The method of Claim 80 wherein said material comprises a
10 polymer.

83. The method of Claim 80 wherein said material comprises BCB.

84. A method of forming a movable structure in a MEMS device,
comprising:

holding the structure at only edges thereof using a polymer; and

15 applying a dry etch to remove said polymer and release said structure.

85. The method of Claim 84 wherein said polymer comprises polyimide.

86. The method of Claim 84 wherein said dry etch is performed using a dry plasma gas.

87. The method of fabricating a MEMS mirror device, comprising:

depositing a reflective material on a mirror structure;

5 depositing a sacrificial layer on said reflective material;

fabricating a mirror device using said mirror structure; and

removing said sacrificial layer.

88. The method of Claim 87 wherein said reflective material comprises gold.

10 89. The method of Claim 87 wherein said sacrificial layer comprises titanium.

90. A method of fabricating a MEMS structure comprising:

depositing oxide on a wafer and selectively removing it;

depositing polysilicon on the remaining oxide;

15 selectively removing the polysilicon using the oxide as an etch stop;
and

removing the remaining oxide.

91. A gimbal mechanism for movably supporting a structure, the gimbal mechanism including two pairs of flexure hinges, each pair defining an axis about which said structure can be rotated, said flexure hinges each
5 having a folded configuration in a cross-section taken generally perpendicular to a respective axis to increase torsional compliance about said respective axis and to decrease compliance in other directions.

92. The gimbal mechanism of Claim 91 wherein each flexure hinge has a generally U-shaped cross-sectional configuration.

10 93. The gimbal mechanism of Claim 91 wherein each flexure hinge has a generally V-shaped cross-sectional configuration.

94. The gimbal mechanism of Claim 91 wherein each flexure hinge has multiple folds.

15 95. The gimbal mechanism of Claim 91 wherein said pairs of flexure hinges comprise an inner pair connecting the structure to an inner gimbal frame, and an outer pair connecting the inner gimbal frame to an outer gimbal frame, and wherein said outer pair have lower torsional compliance compared to the inner pair.

20 96. The gimbal mechanism of Claim 91 wherein each flexure hinge comprises a plurality of springs, and wherein said springs are arranged in a folded configuration in a top view thereof.

97. A gimbal mechanism for movably supporting a structure, the gimbal mechanism including two pairs of flexure hinges, each pair defining an axis about which said structure can be rotated, said flexure hinges each comprising multiple springs in a folded configuration, each spring also
5 having a folded configuration in a cross-section taken generally perpendicular to a respective axis to increase torsional compliance about said respective axis and to decrease torsional compliance in other directions.

98. The gimbal mechanism of Claim 97 wherein each spring has a generally U-shaped cross-sectional configuration.

10 99. The gimbal mechanism of Claim 97 wherein each spring has a generally V-shaped cross-sectional configuration.

100. The gimbal mechanism of Claim 97 wherein each spring has multiple folds.

15 101. The gimbal mechanism of Claim 97 wherein said pairs of flexure hinges comprise an inner pair connecting the structure to an inner gimbal frame, and an outer pair connecting the inner gimbal frame to an outer gimbal frame, and wherein said outer pair have lower torsional compliance compared to the inner pair.

20 102. The package of Claim 59 wherein the MEMS mirror array device is electrically connected to said base by a combination of flip chip bump bonding and wire-bonding.

103. The package of Claim 59 wherein the thickness of said window

of the lid and the distance between said window and the MEMS mirror array device is optimized to avoid negative optical interference between light reflected from said window and any other light beams.

104. A method of fabricating a through-wafer interconnect device for
5 a MEMS device, comprising:

providing a silicon-on-insulator wafer having a device layer and a handle layer;

bonding the device layer of the silicon-on-insulator wafer to a wafer having a plurality of through-holes;

10 dissolving the handle layer of the silicon-on-insulator wafer; and

selectively etching away the device layer to leave silicon membranes extending over said through-holes.

105. A method of depositing a thin film on the back of a MEMS device, comprising:

15 forming a shadow mask from a silicon wafer;

positioning the shadow mask on the back of the device; and

evaporating material forming said thin film through said shadow mask.

106. The method of Claim 105 wherein said material comprises gold.

107. The MEMS mirror device of Claim 36 wherein said one pair of electrodes and said mirror have a corresponding comb-fingers arrangement.

108. A method of fabricating a MEMS mirror-gimbal structure,
5 comprising:

providing a silicon-on-insulator wafer having a device layer and a handle layer;

patterning the device layer to form flexure hinges of a gimbal mechanism;

10 performing selective epitaxial growth of silicon on said device layer to form a thickened silicon layer; and

patterning the thickened silicon layer to form a mirror and a gimbal frame of said gimbal mechanism.

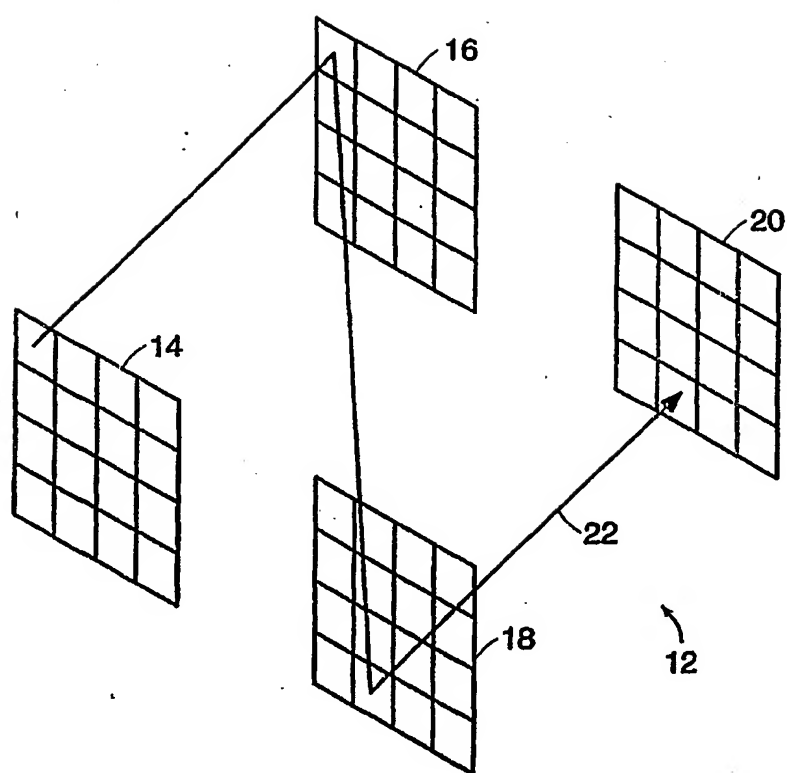


FIG. 1
PRIOR ART

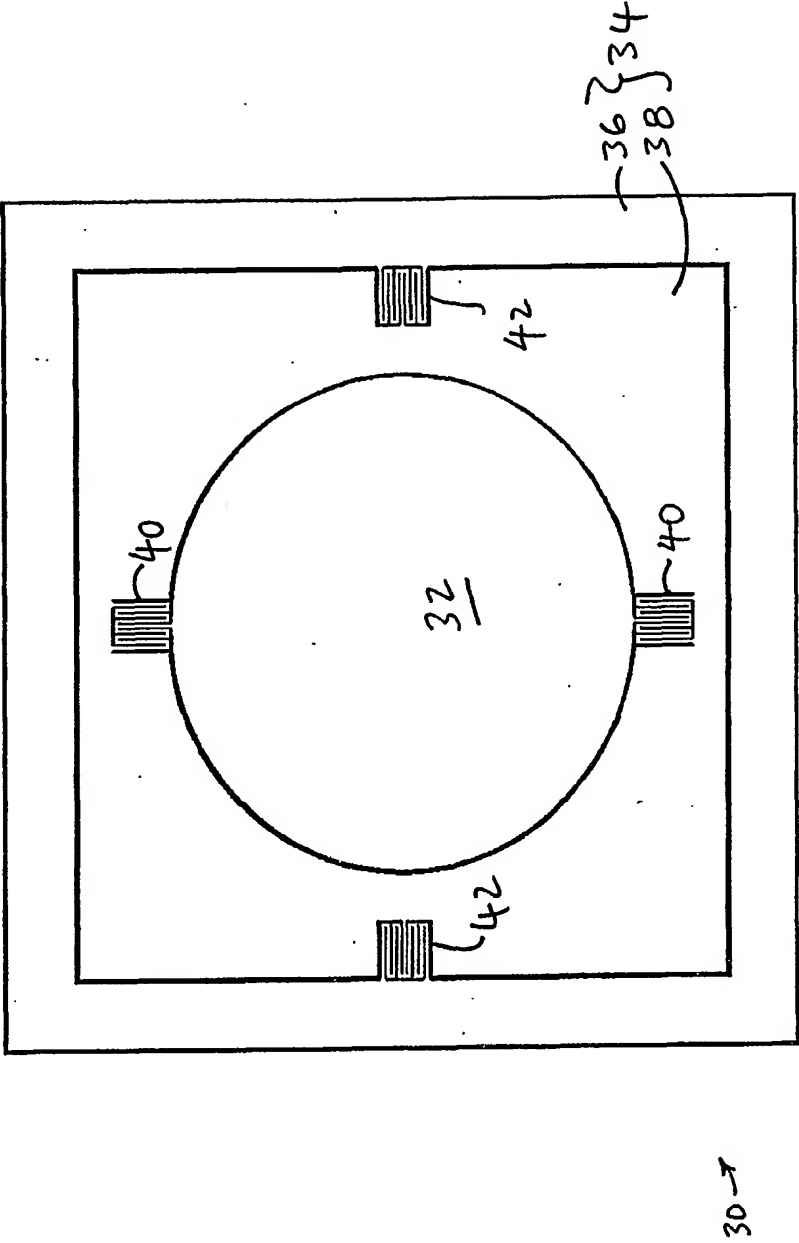


FIG. 2

FIG. 3

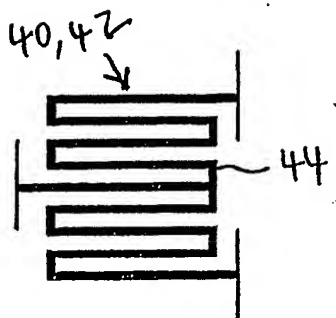


FIG. 4A

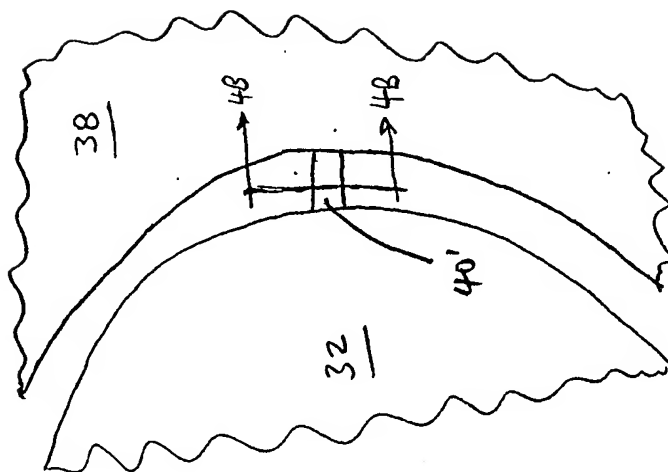
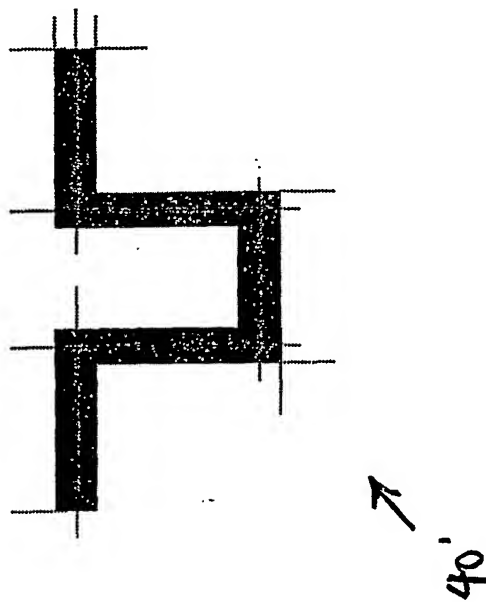
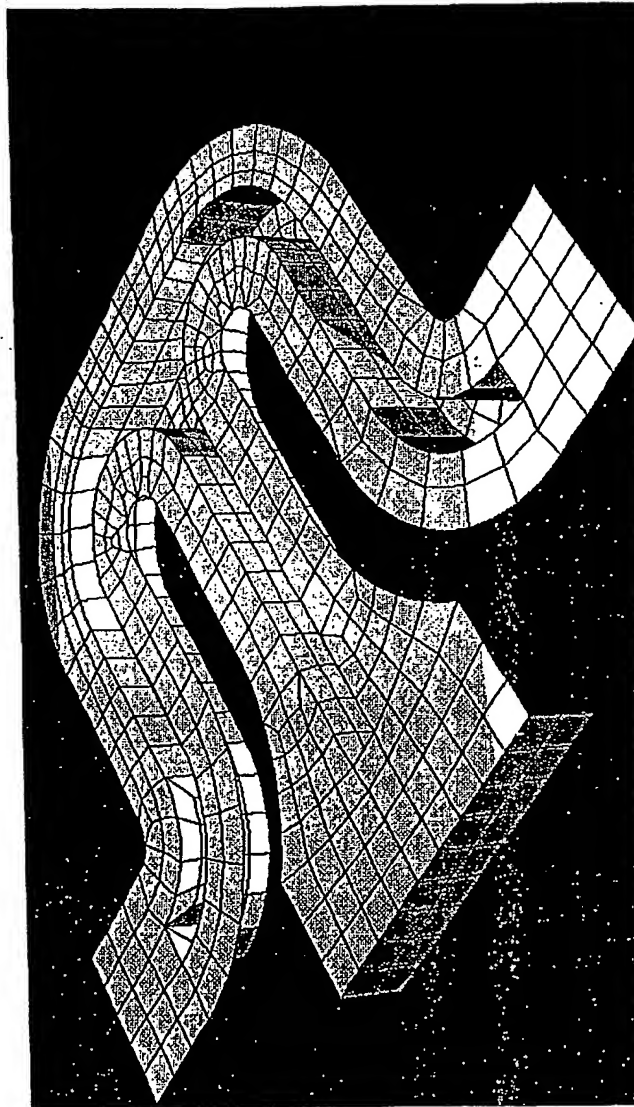


Figure 4B

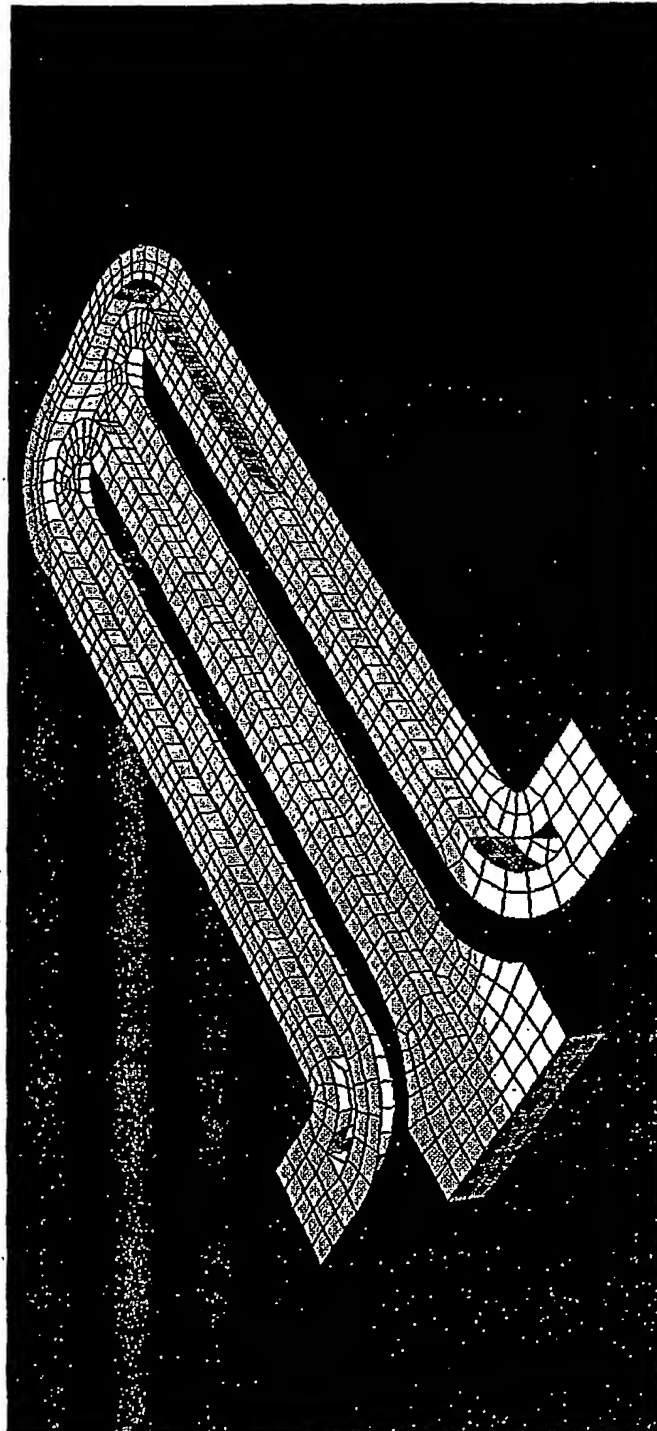




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FIG. 5A

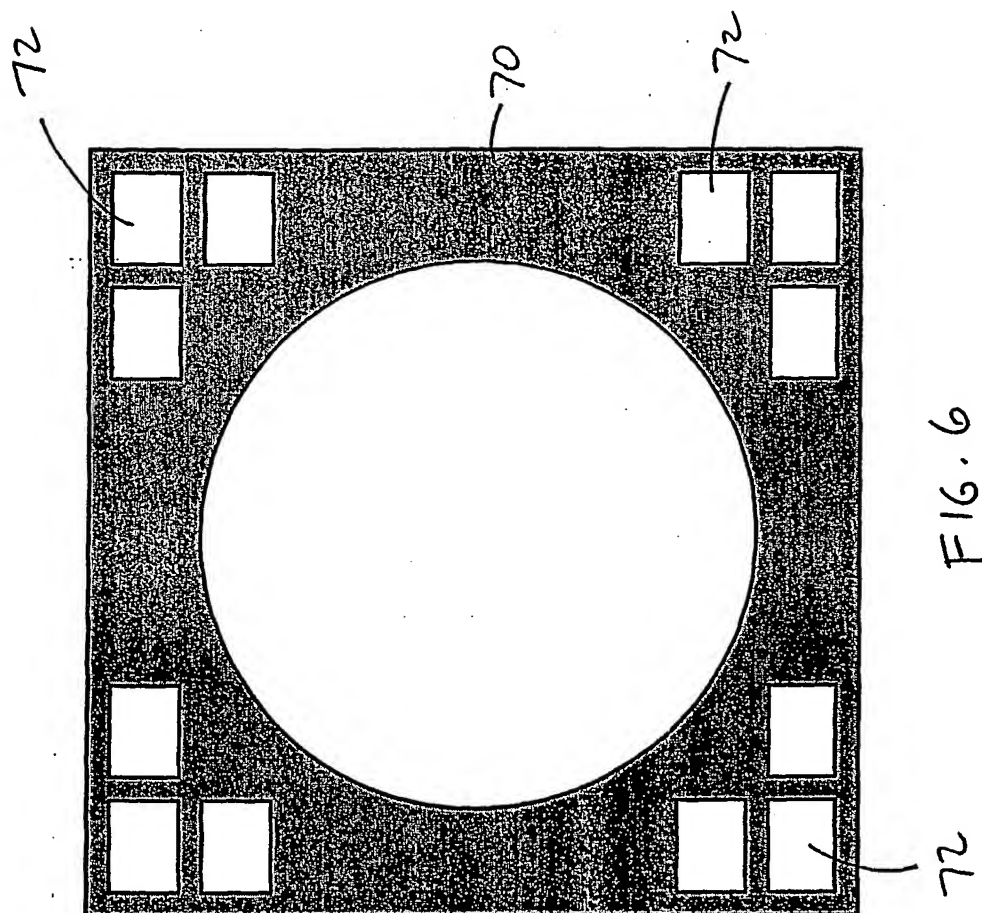
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625

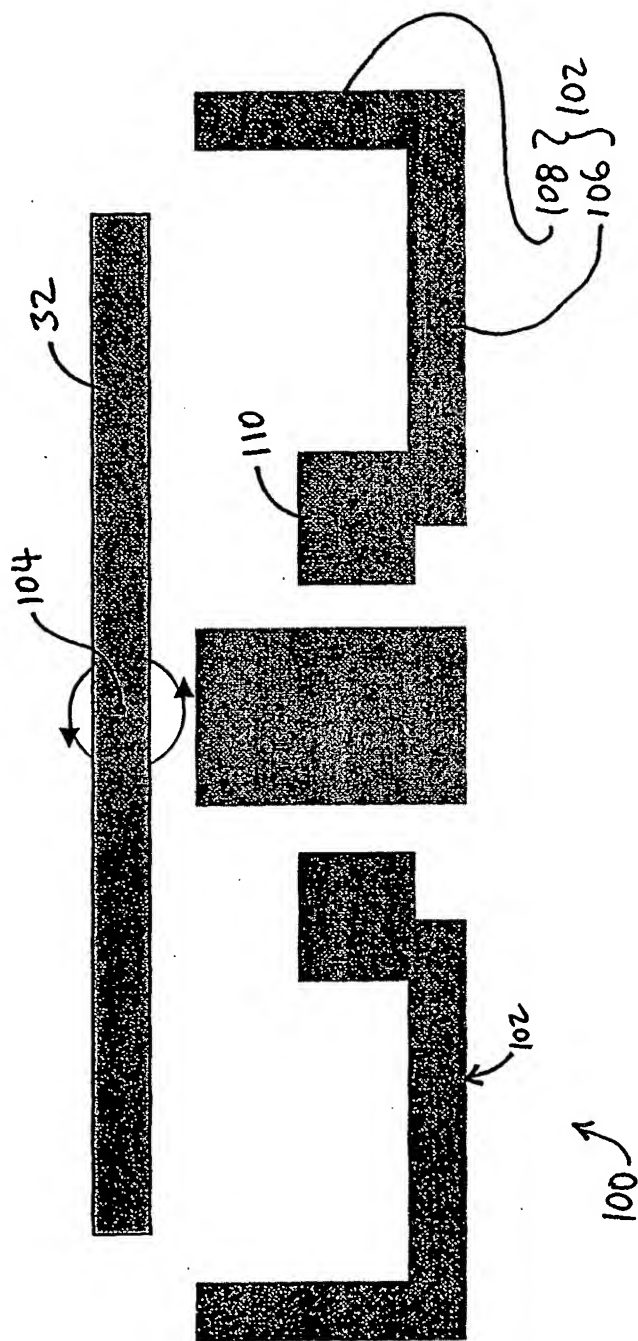
FIG. 5B

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BEST AVAILABLE COPY

Figure 7A



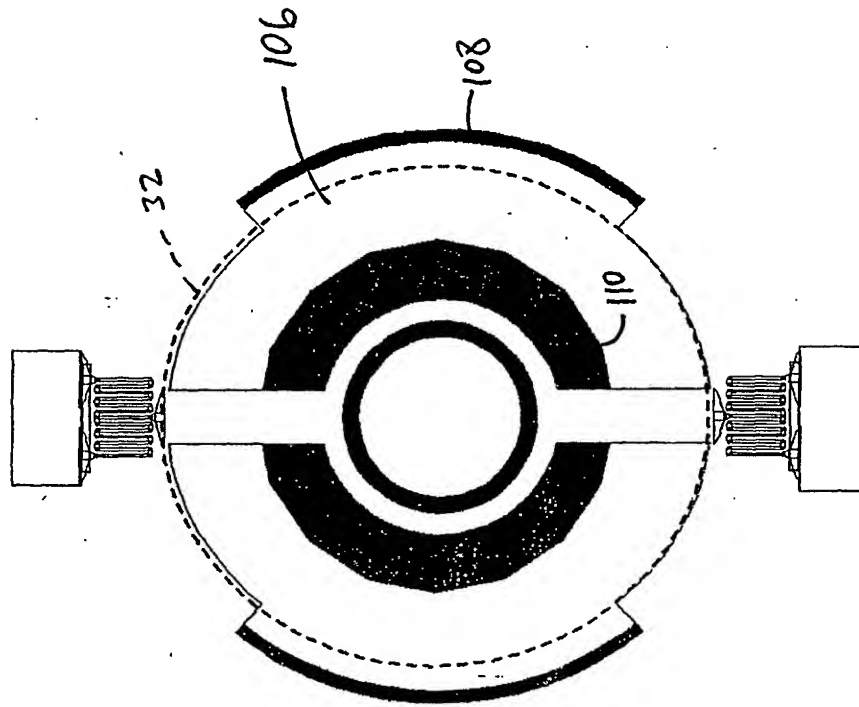


FIG. 7B

Figure 8A

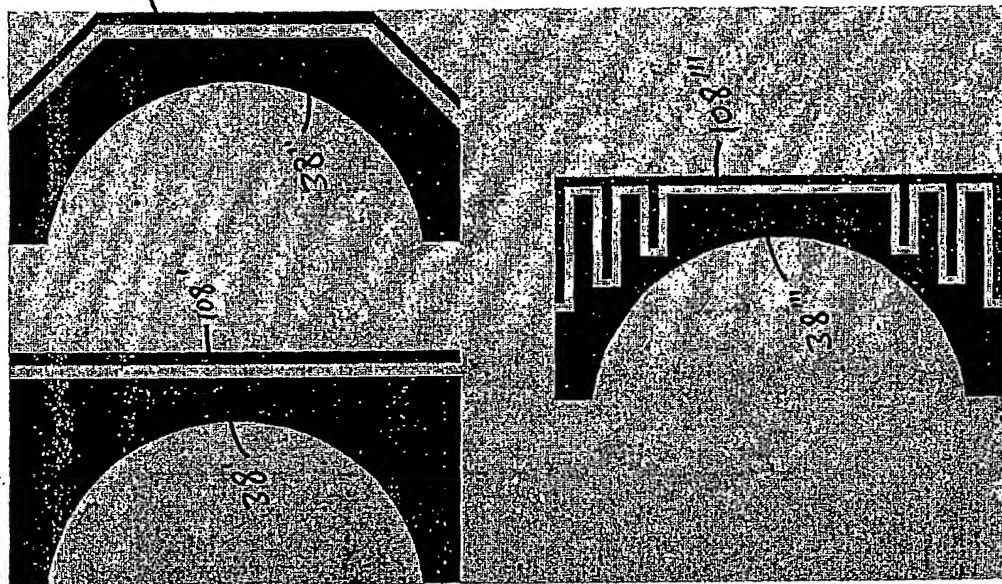


Figure 8B

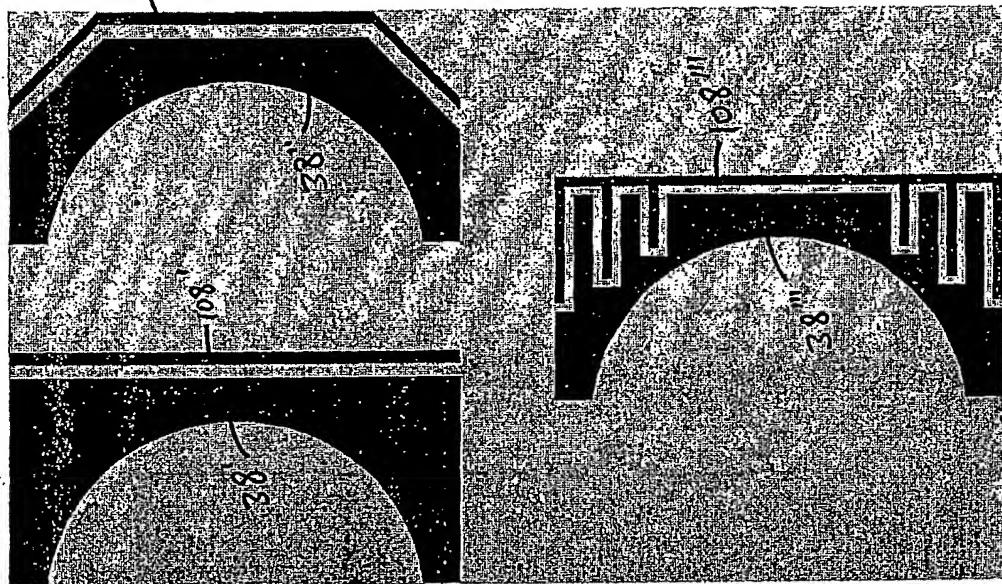
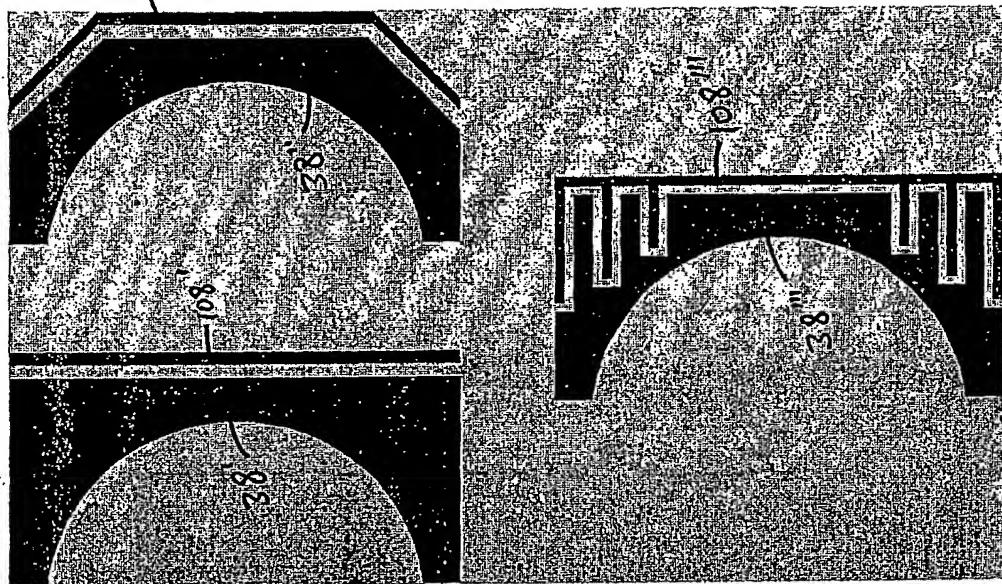


Figure 8C



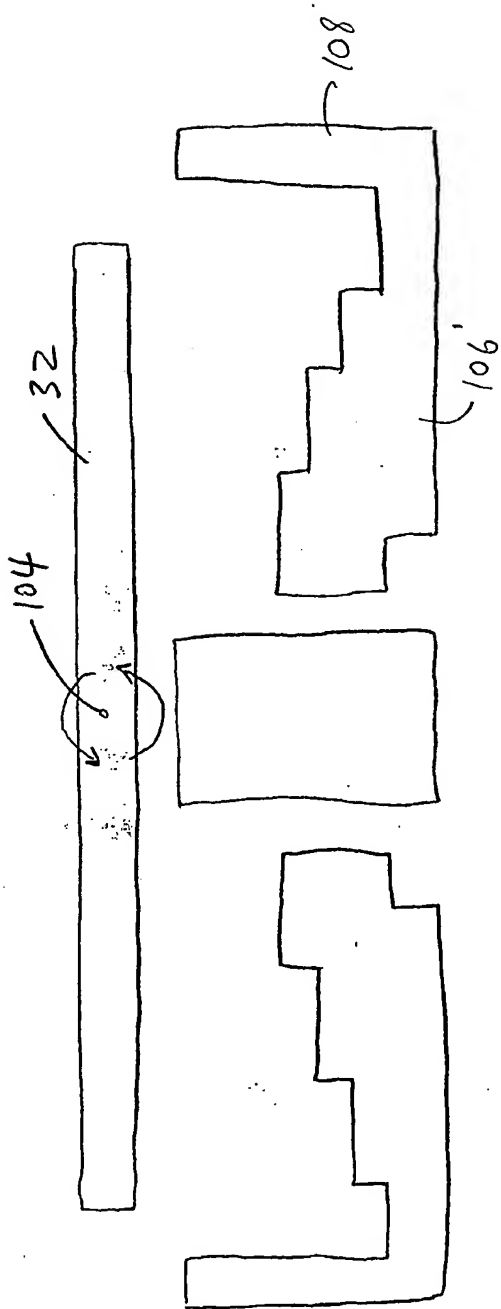


FIG. 9

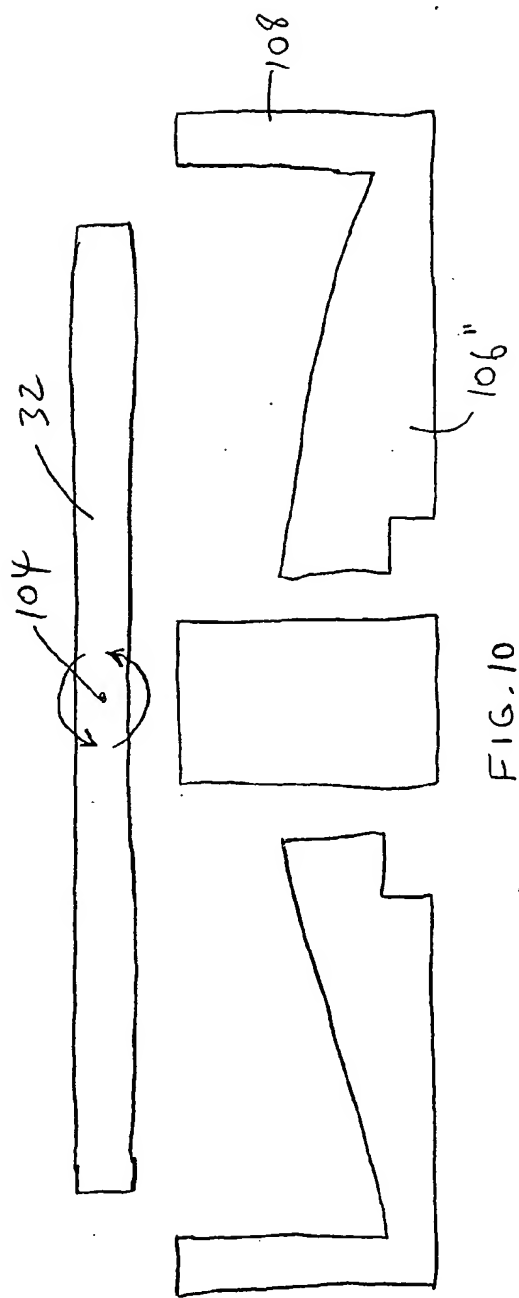


FIG. 10

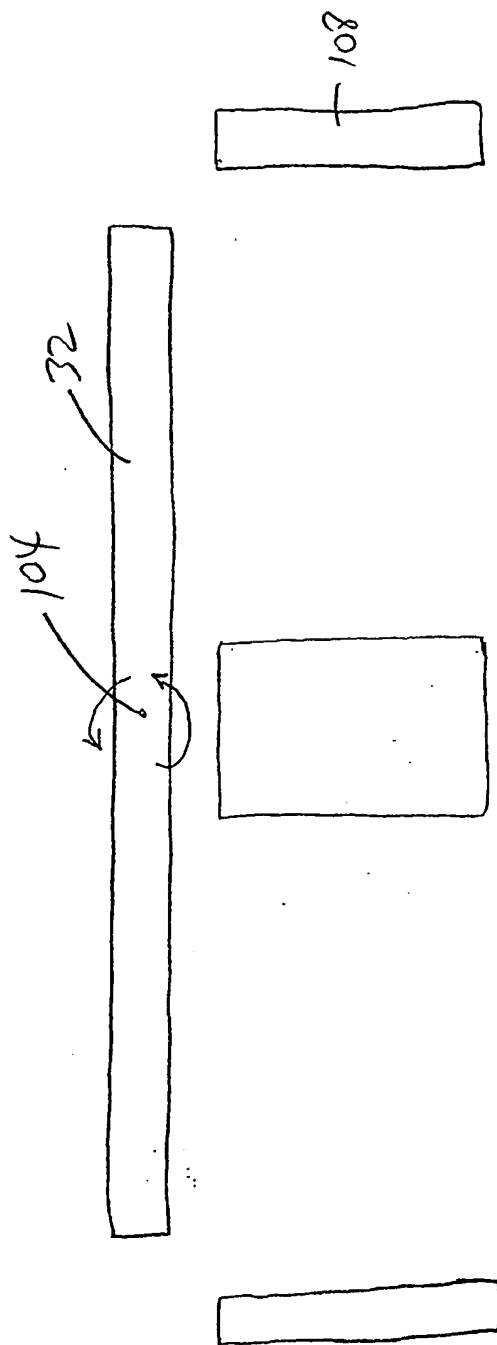


FIG. 11

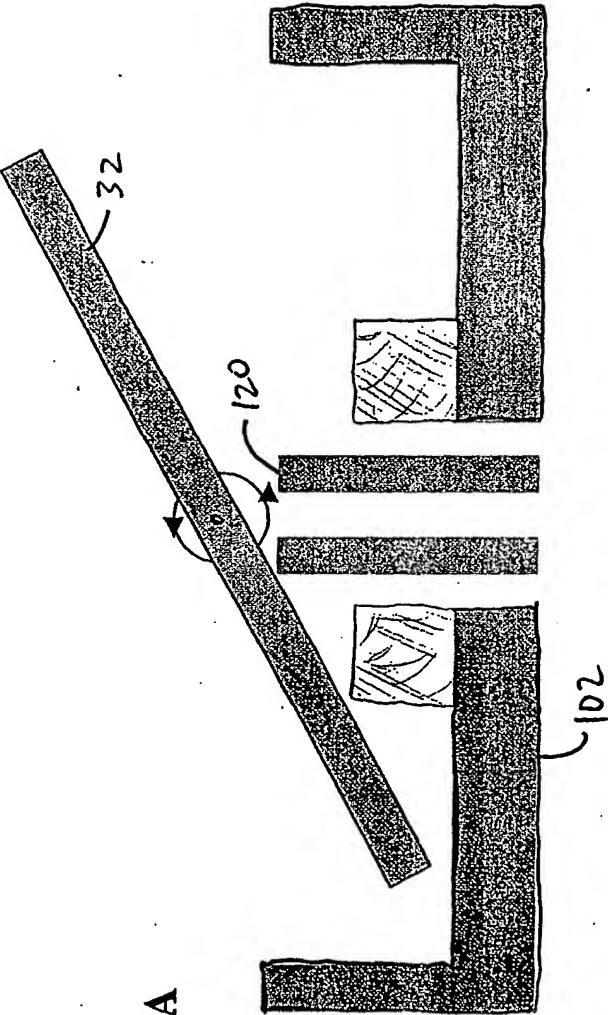


Figure 12A

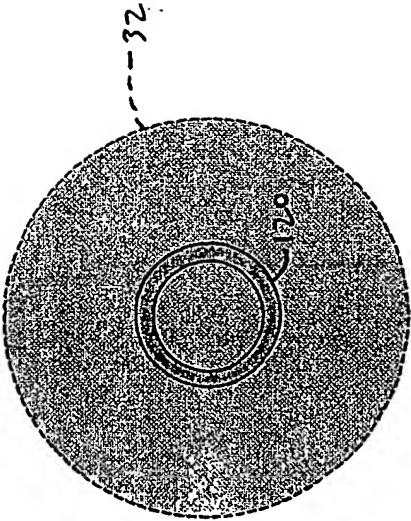


Figure 12B

Figure 13A

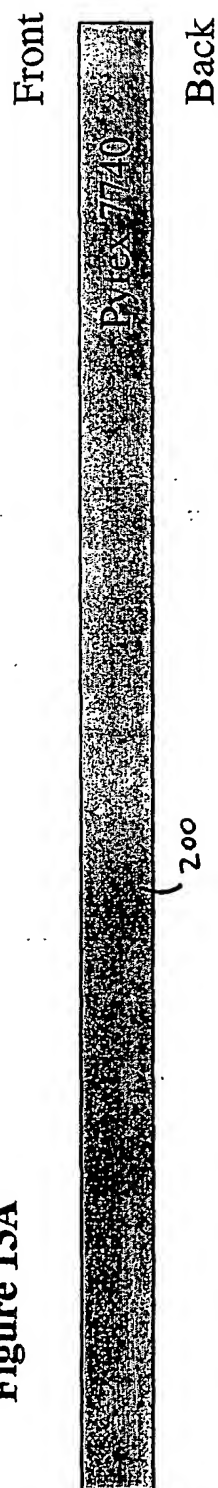


Figure 13B

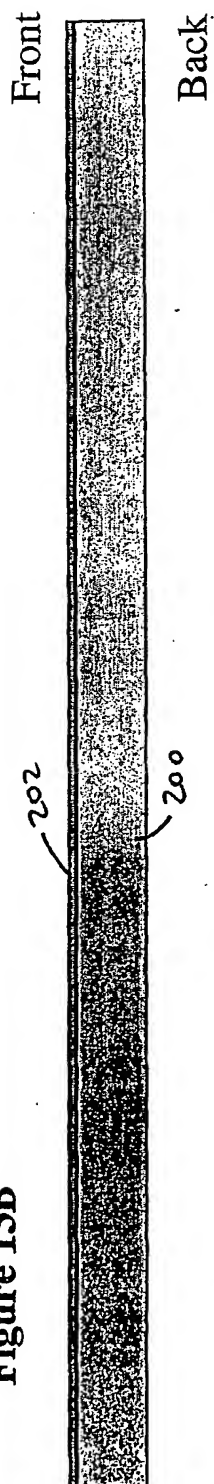


Figure 13C

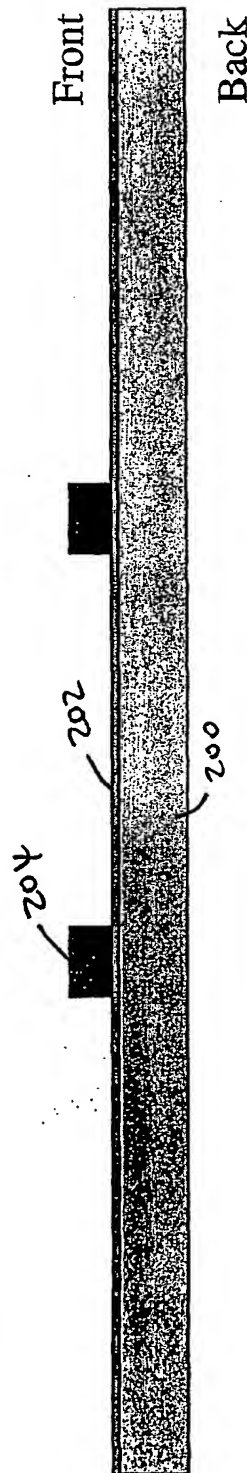


Figure 13D

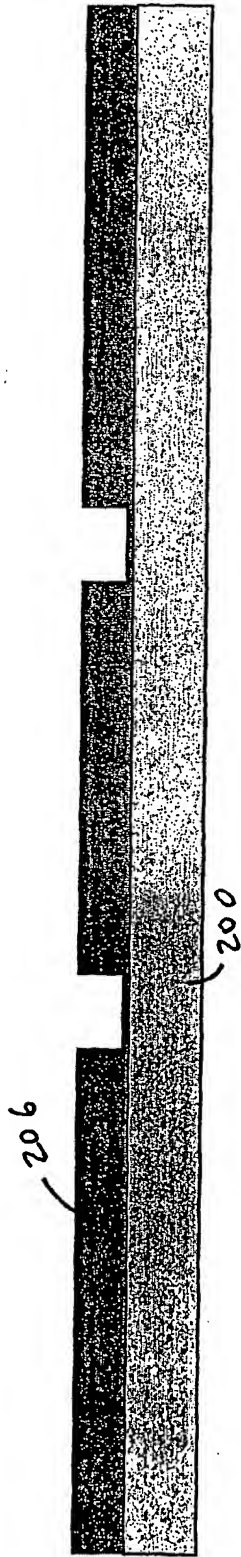


Figure 13E

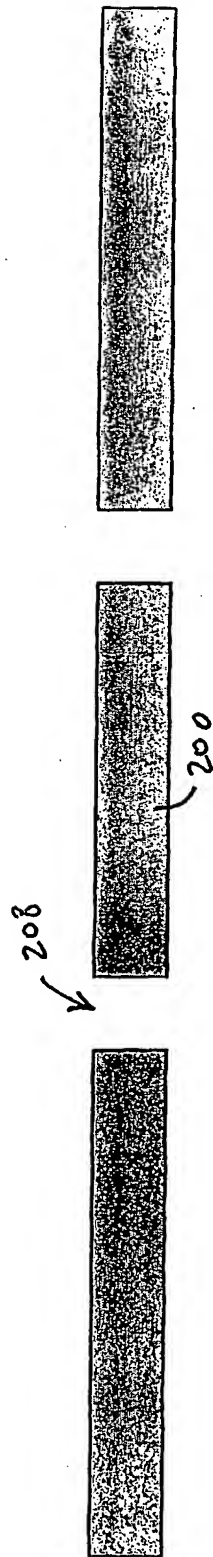


Figure 13F

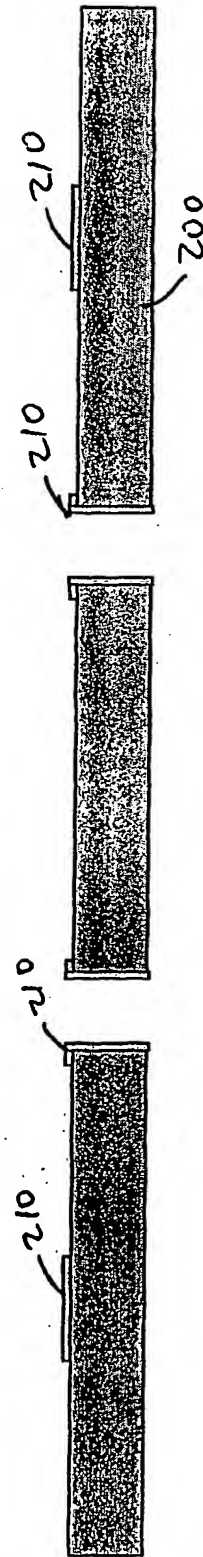


Figure 13G

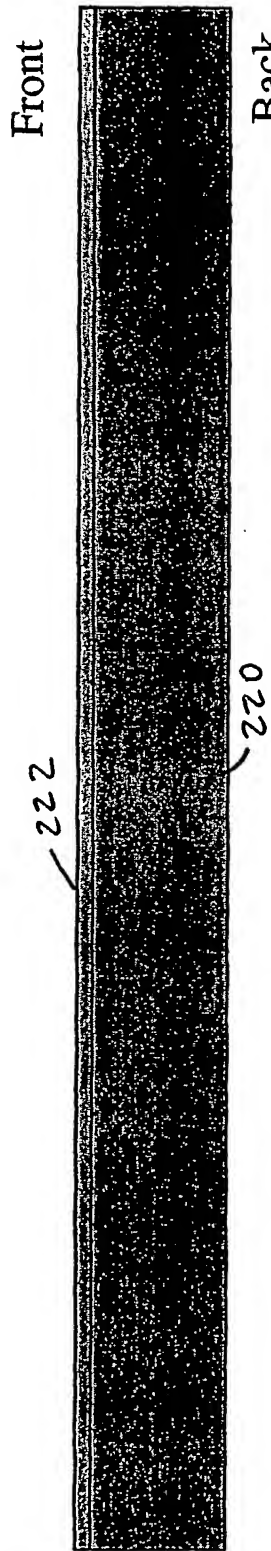


Figure 13H

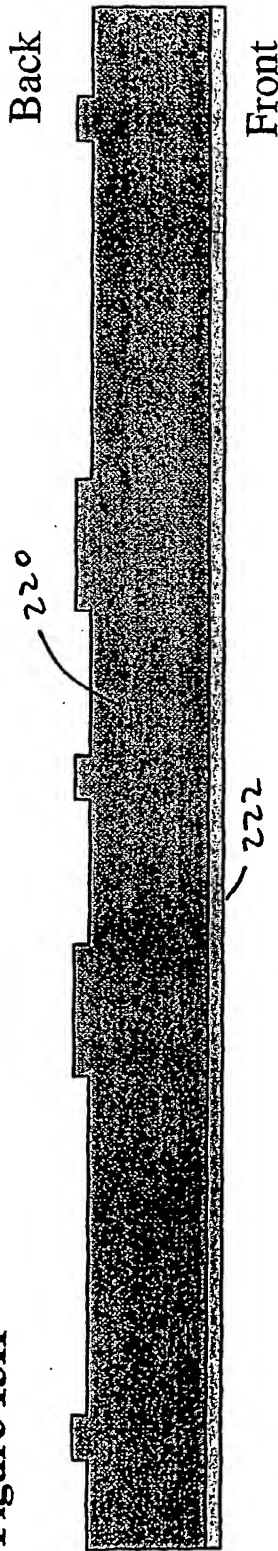


Figure 13I

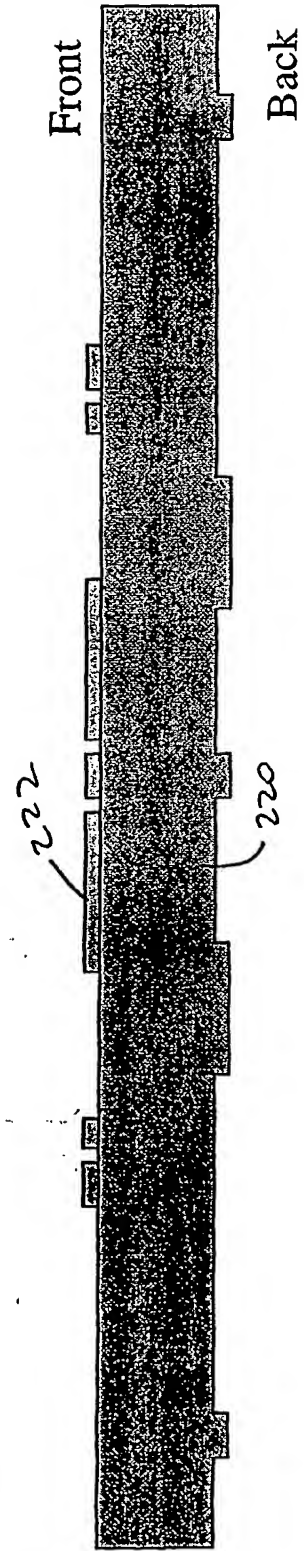


Figure 13J

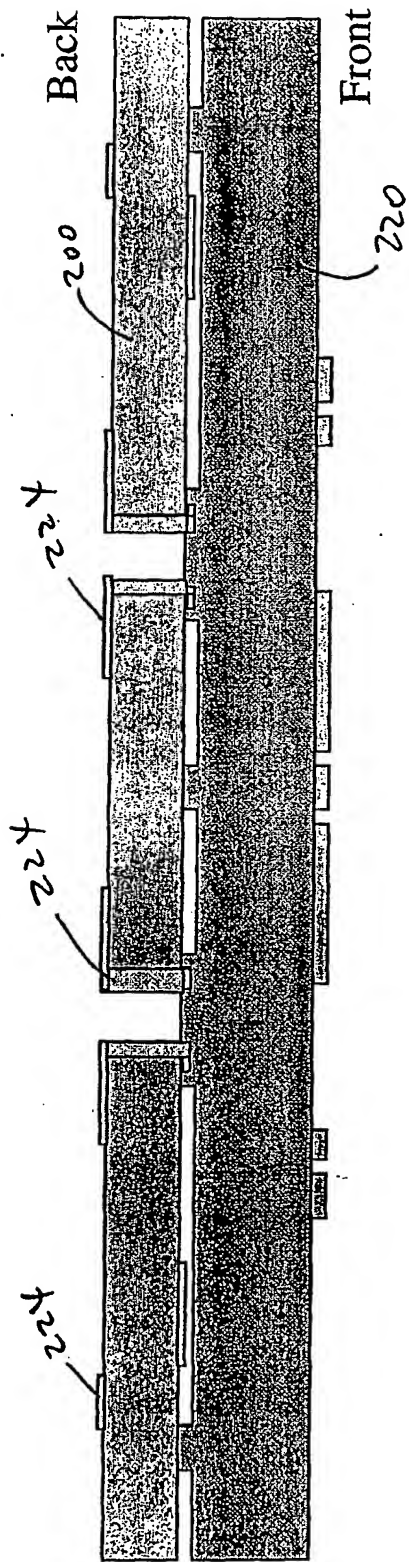


Figure 13K

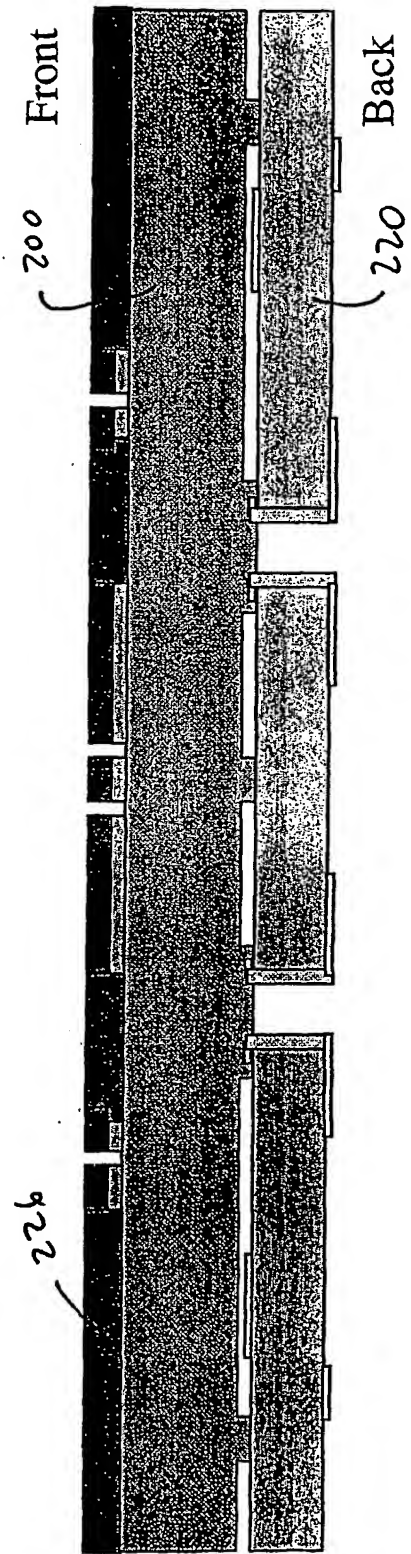


Figure 13L

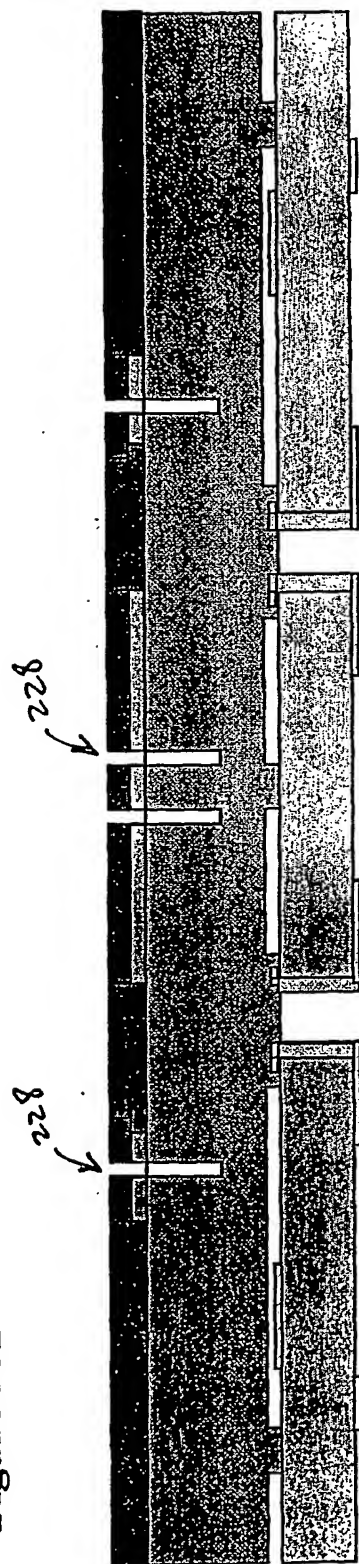
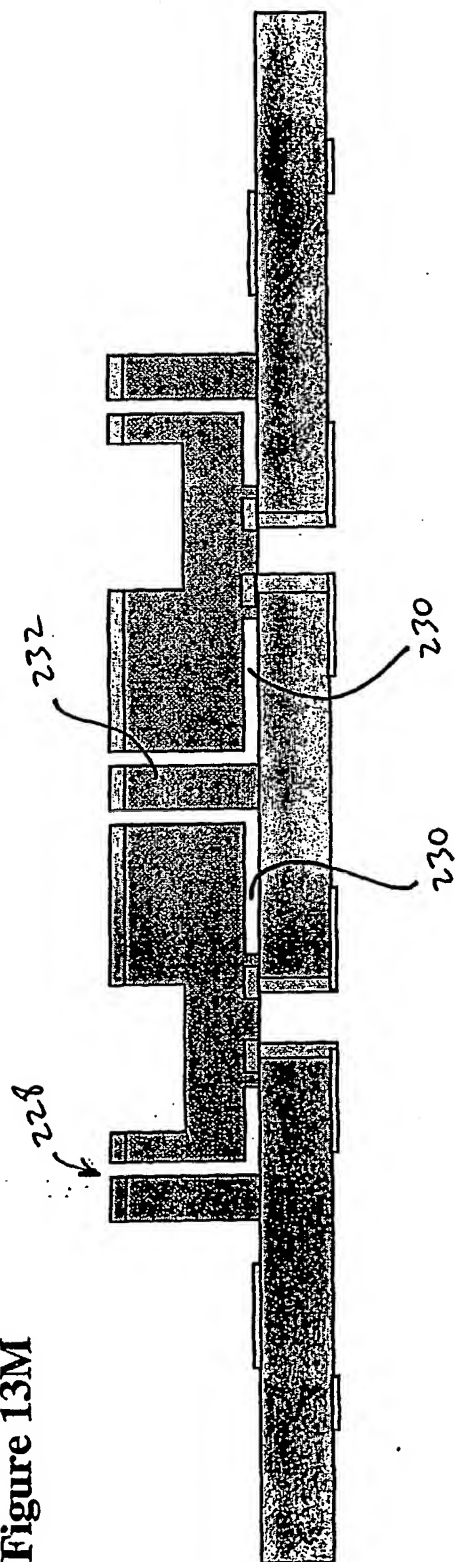


Figure 13M



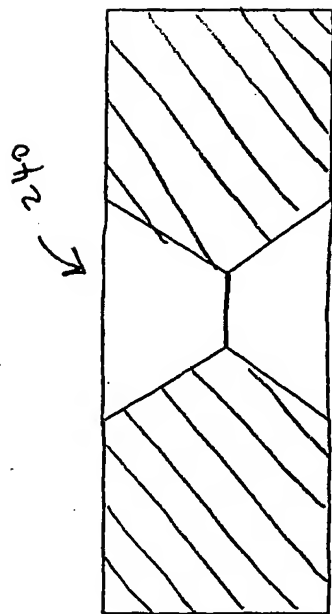


FIG. 14A

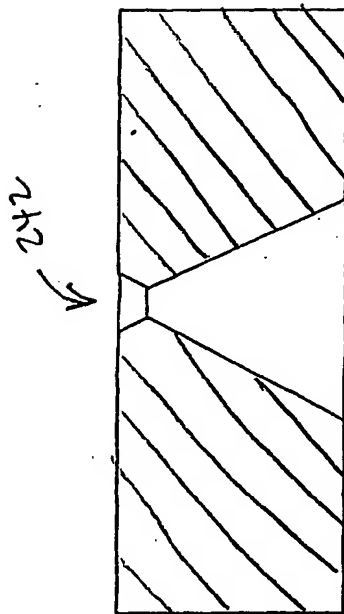


FIG. 14B

Figure 15A

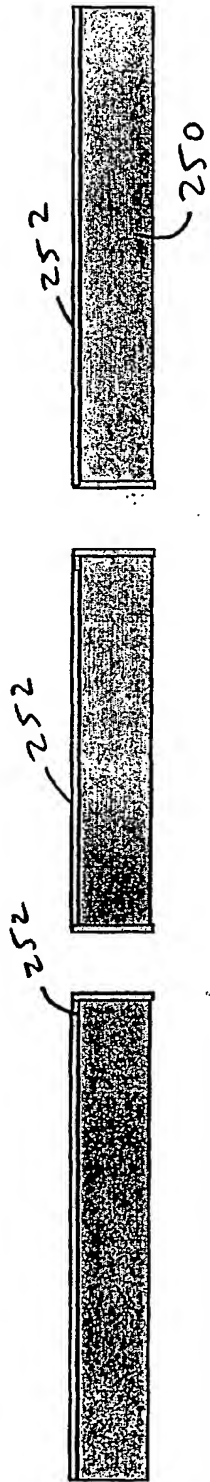


Figure 15B

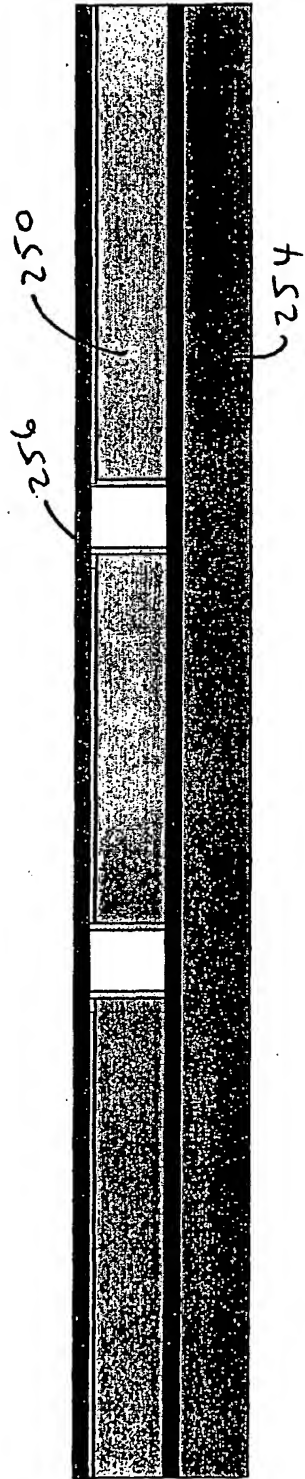


Figure 15C

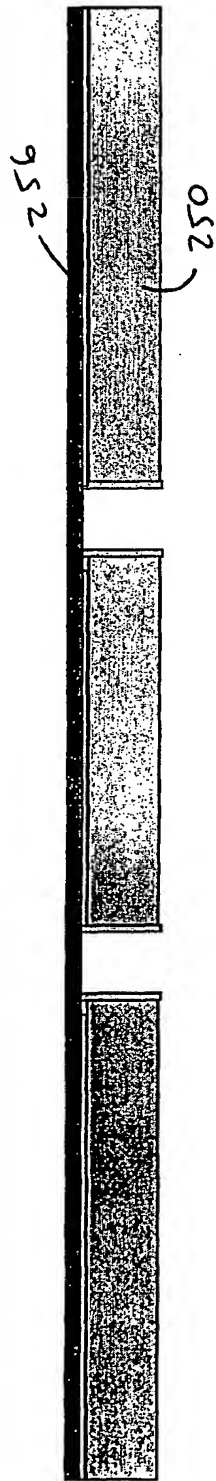


Figure 15D

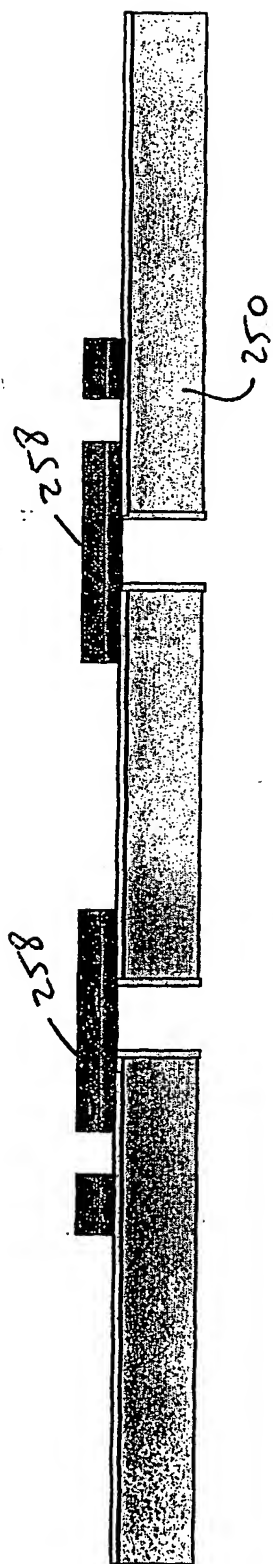


Figure 15E

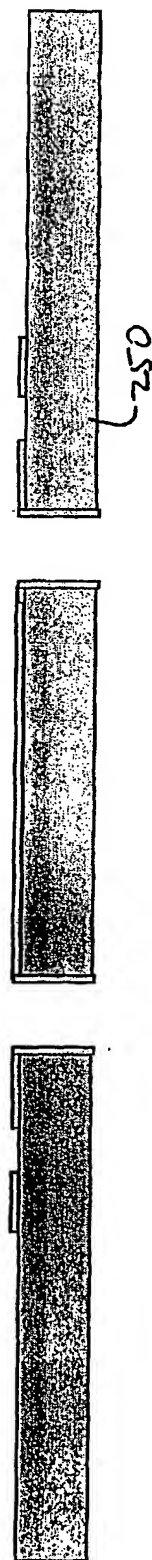


Figure 16A

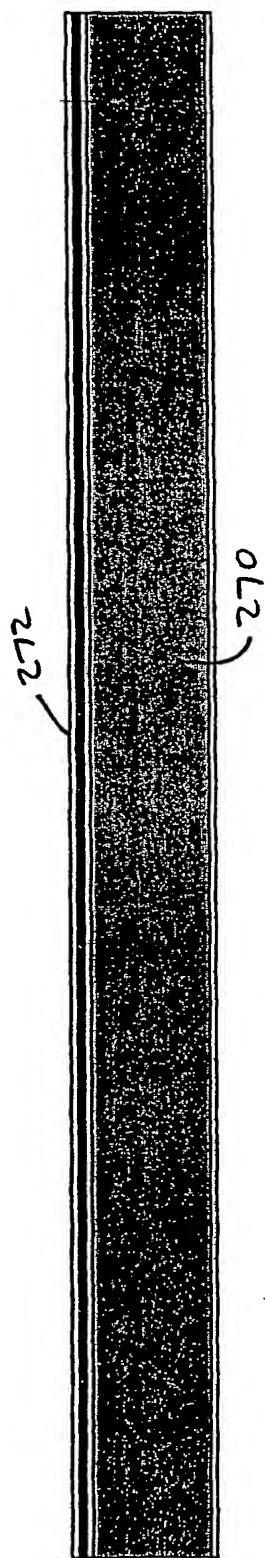


Figure 16B

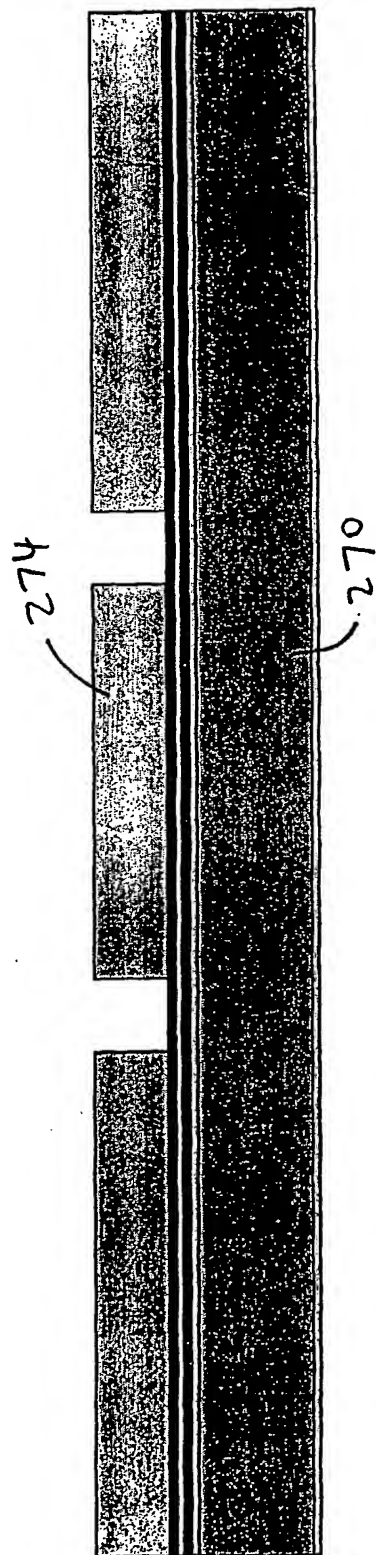


Figure 16C

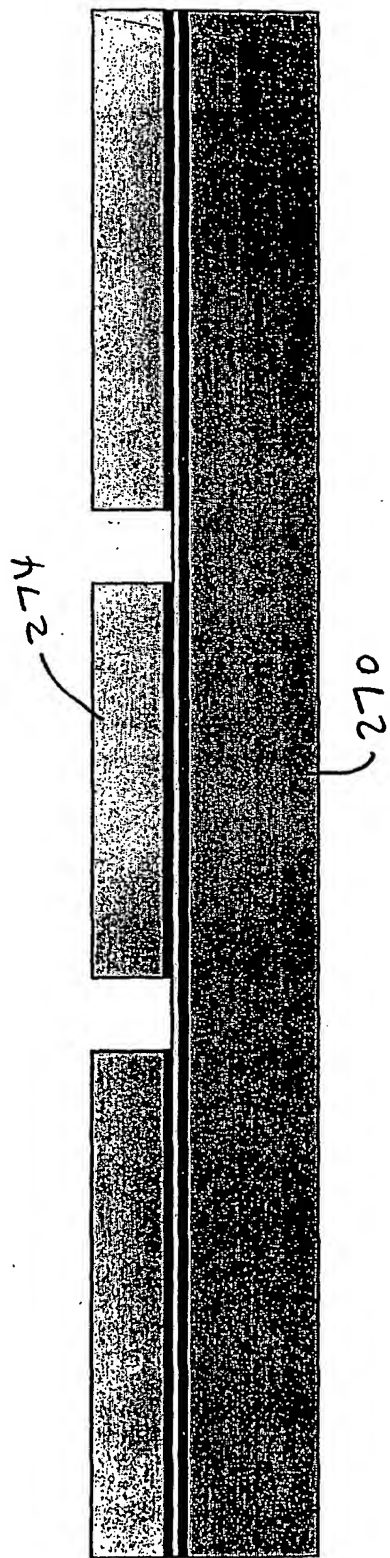


Figure 16D

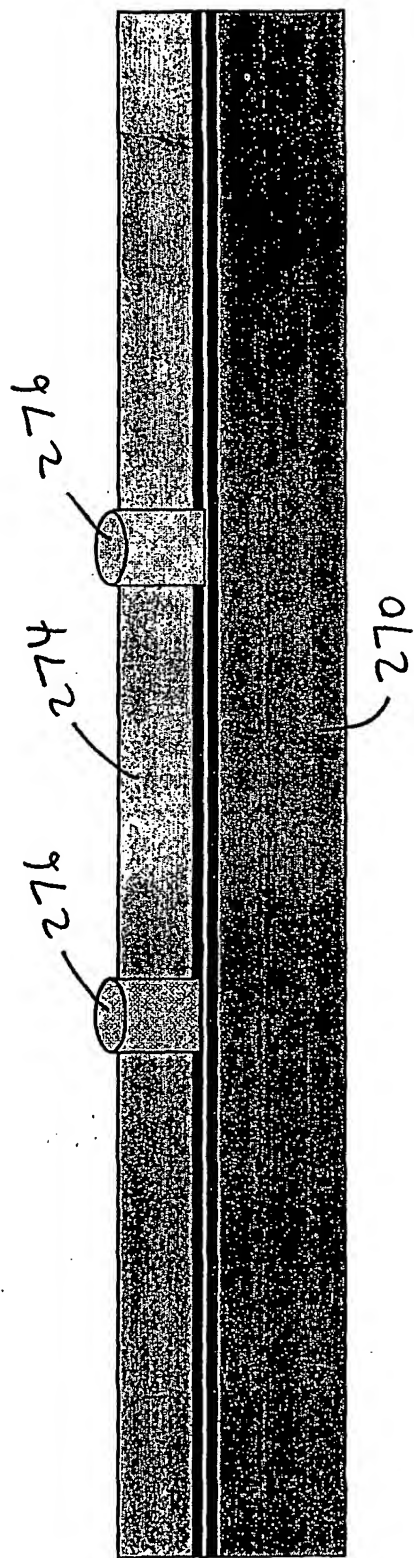


Figure 16E

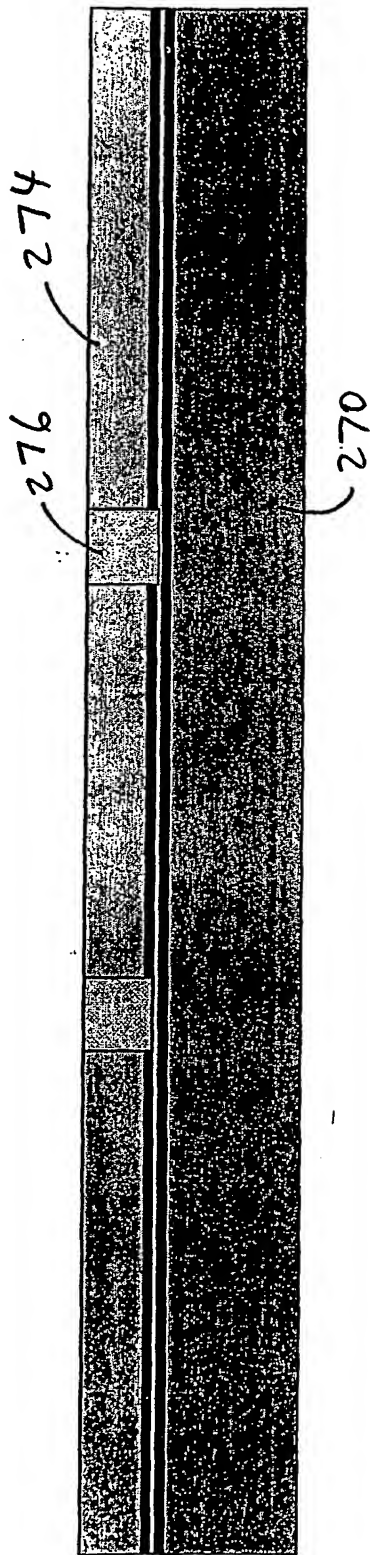


Figure 16F

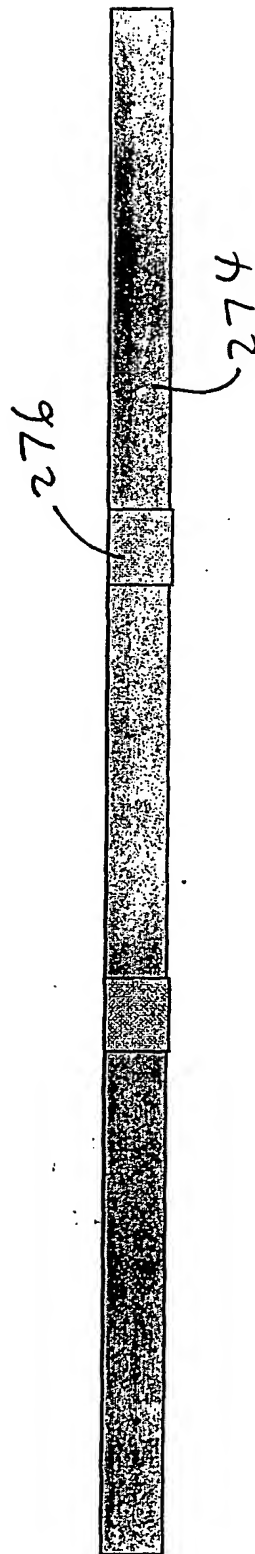


Figure 17A

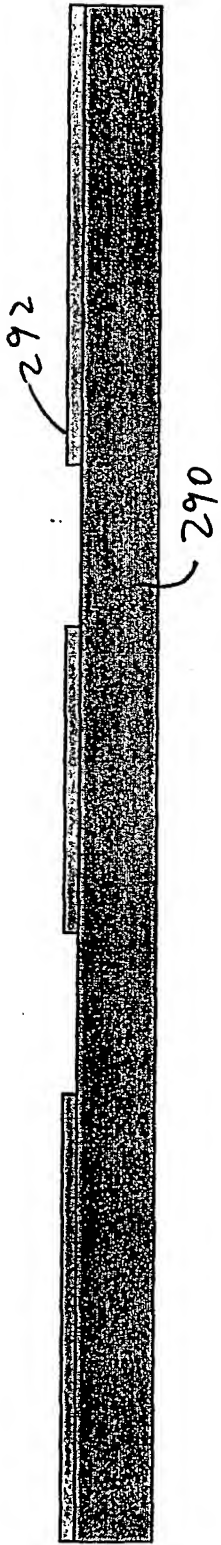


Figure 17B

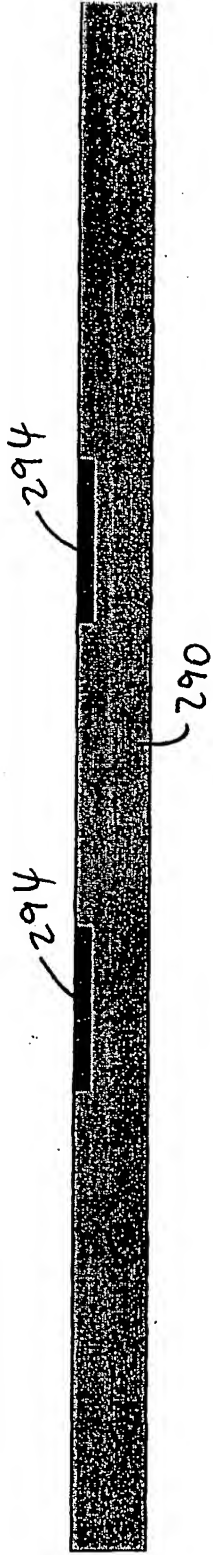


Figure 17C

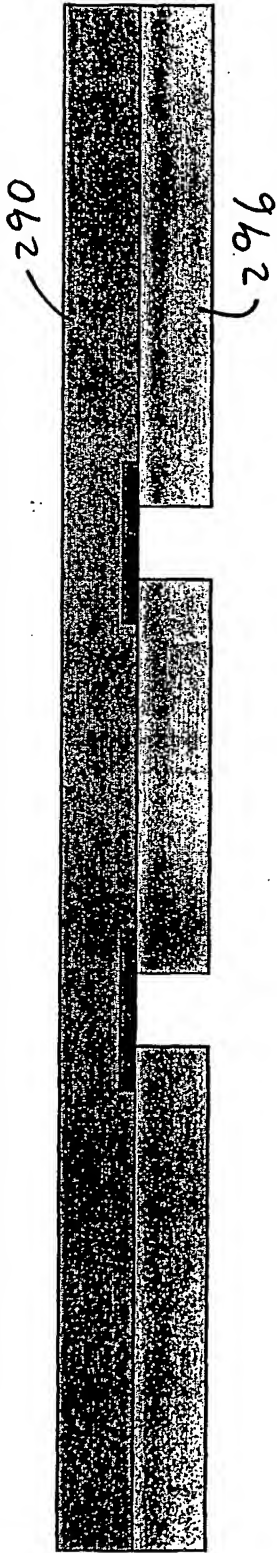


Figure 17D

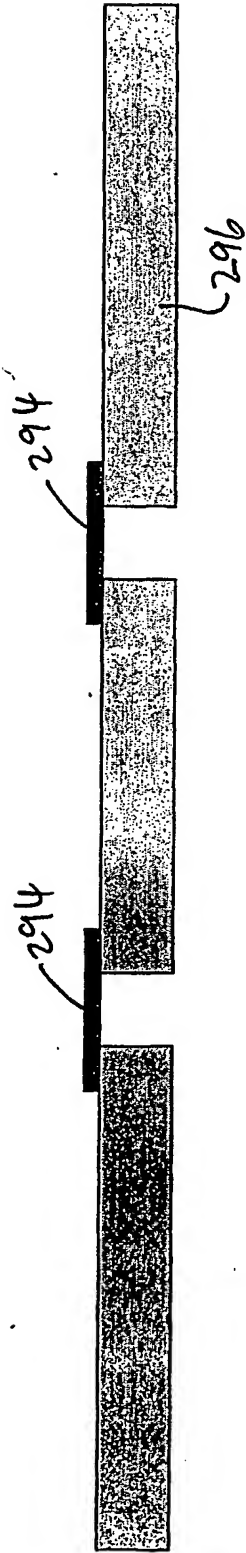


Figure 18A

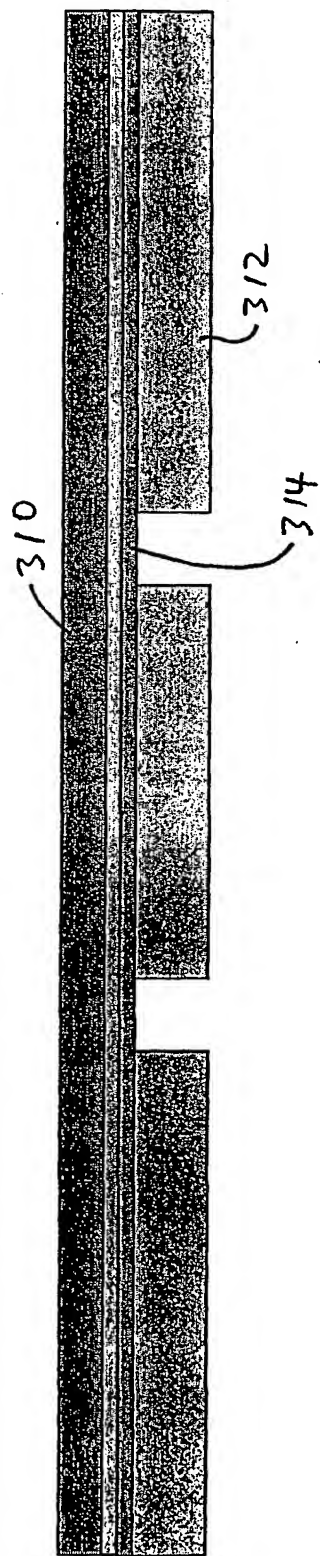


Figure 18B

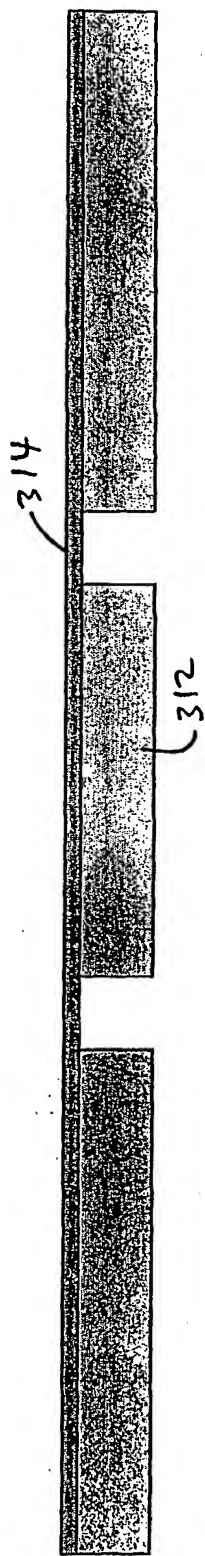


Figure 18C

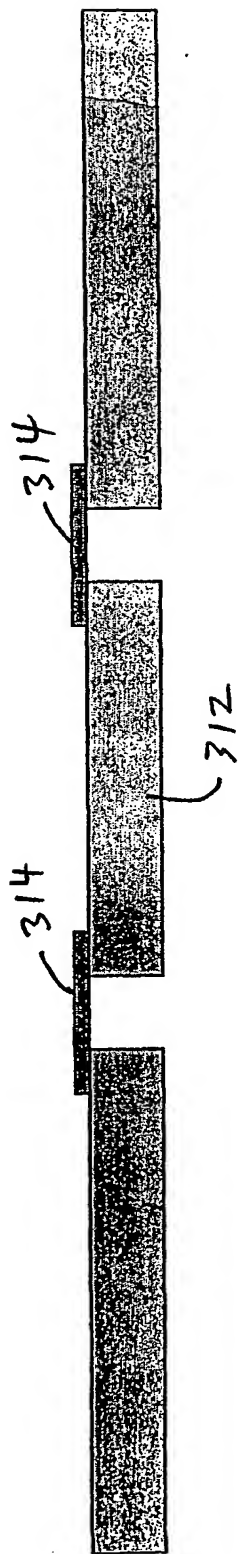


Figure 19A

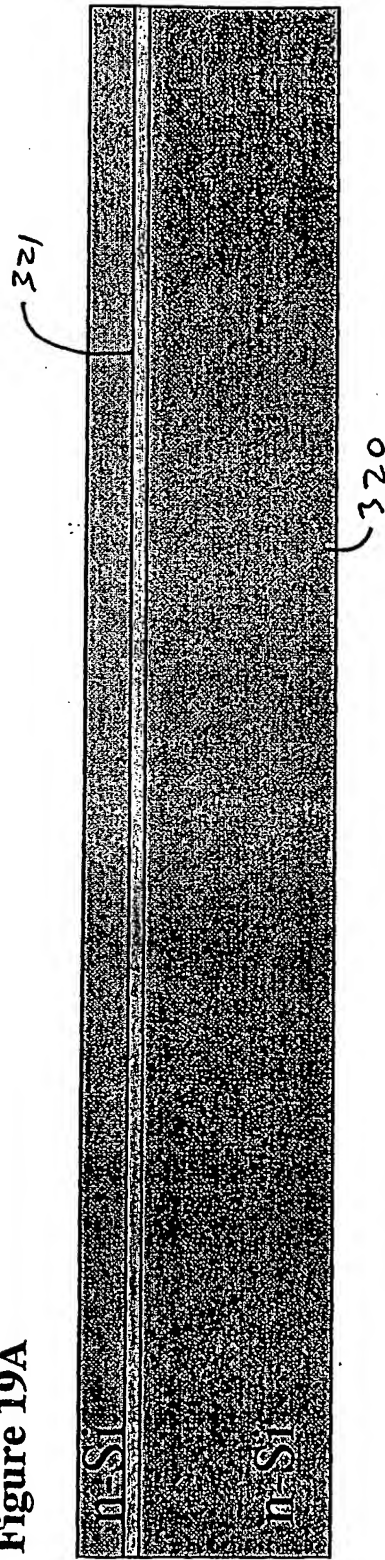


Figure 19B

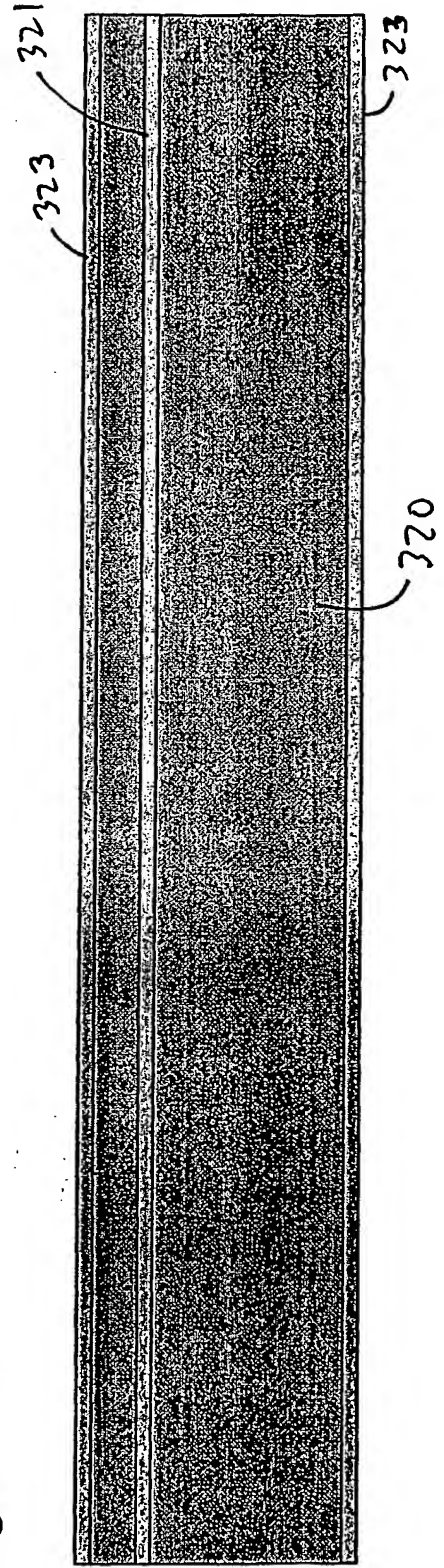


Figure 19C

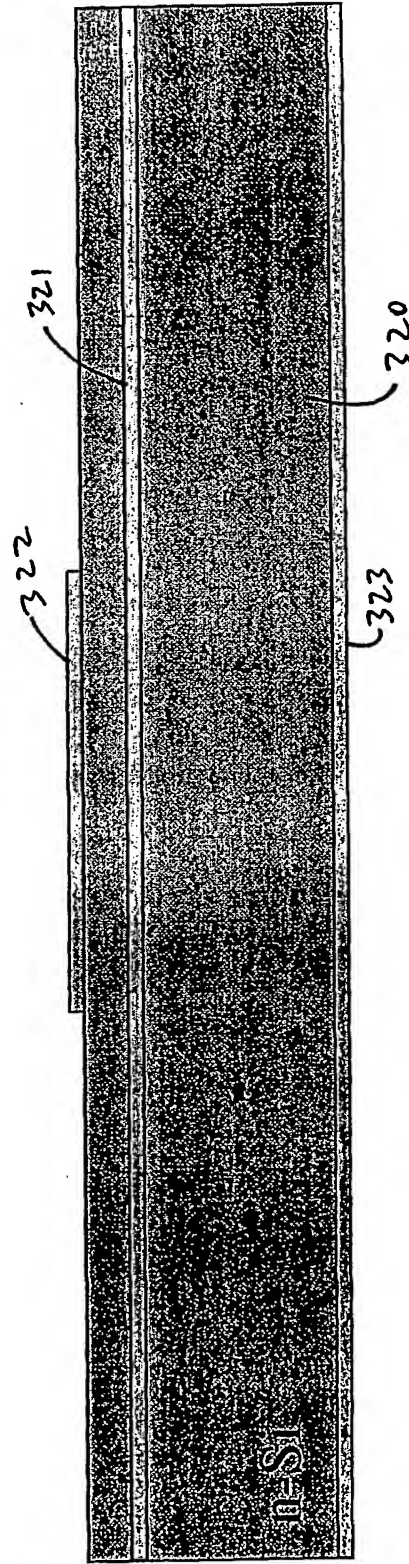


Figure 19D

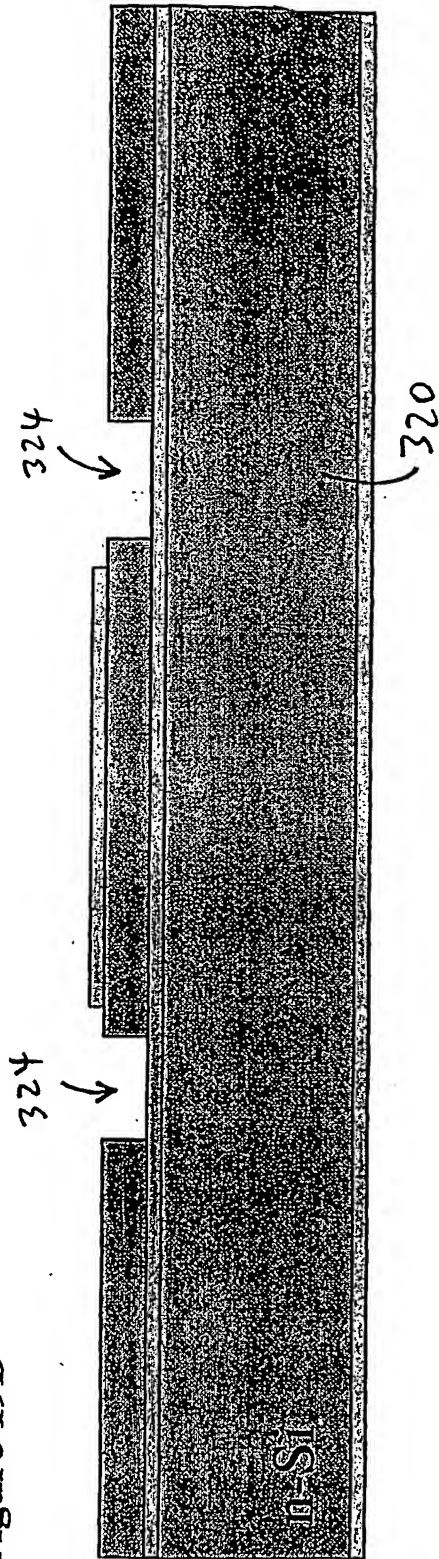


Figure 19E

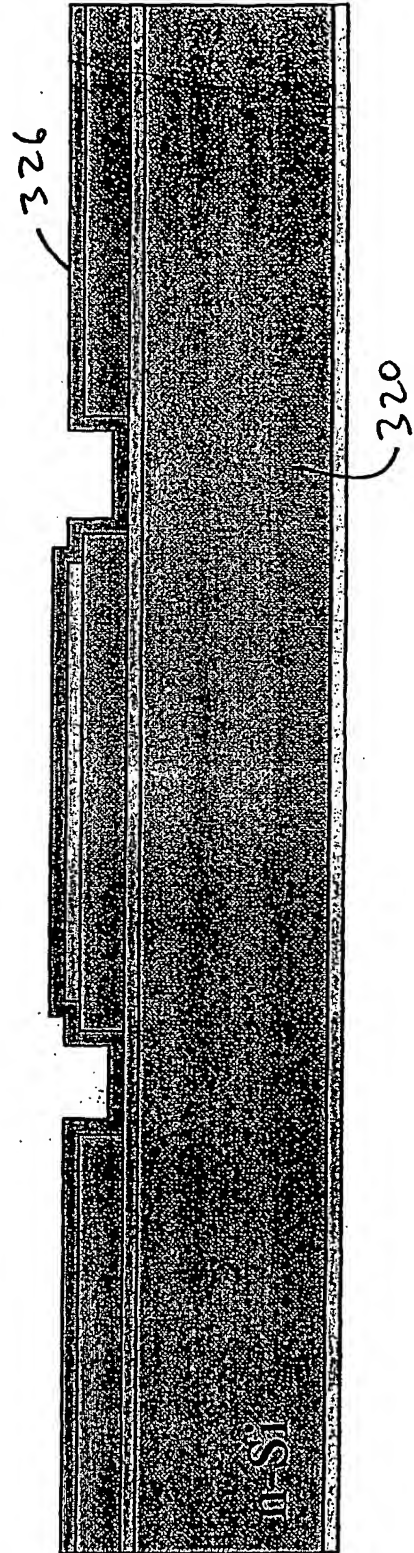


Figure 19F

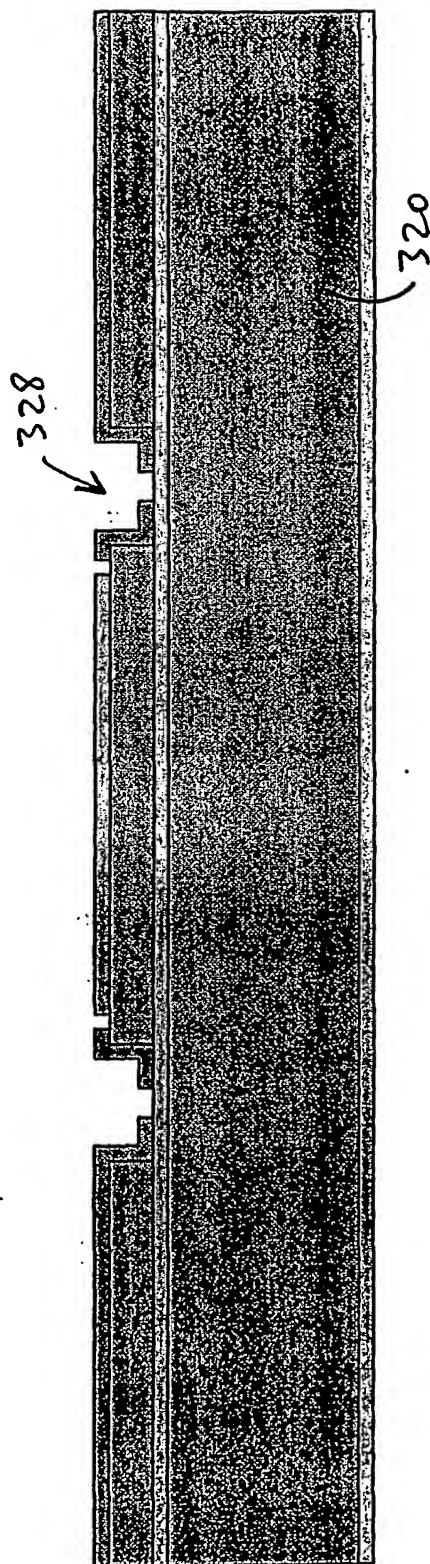


Figure 19G

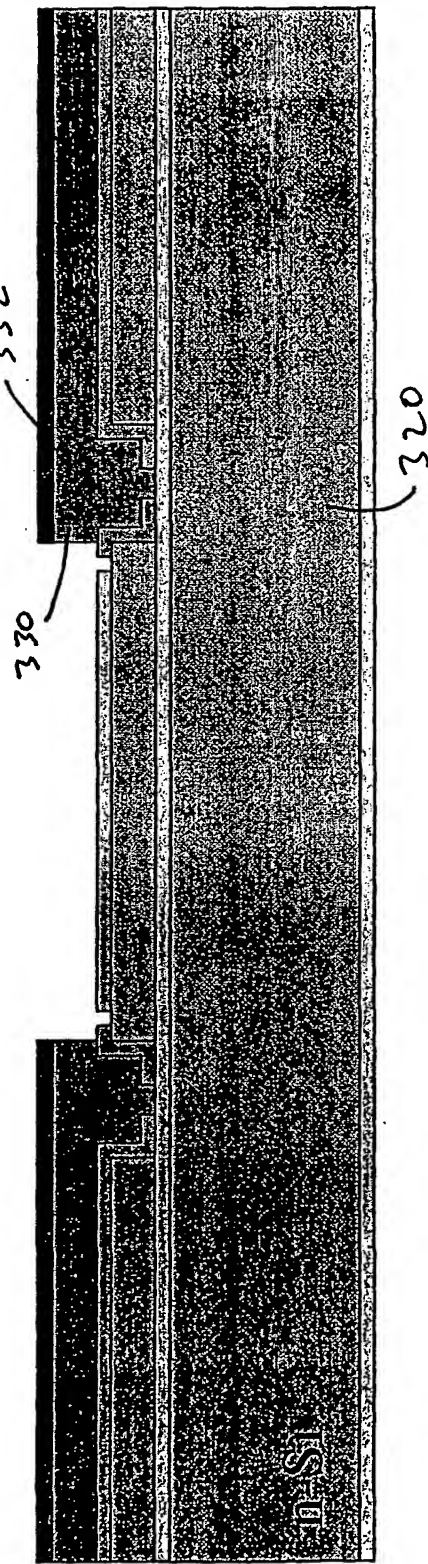


Figure 19H

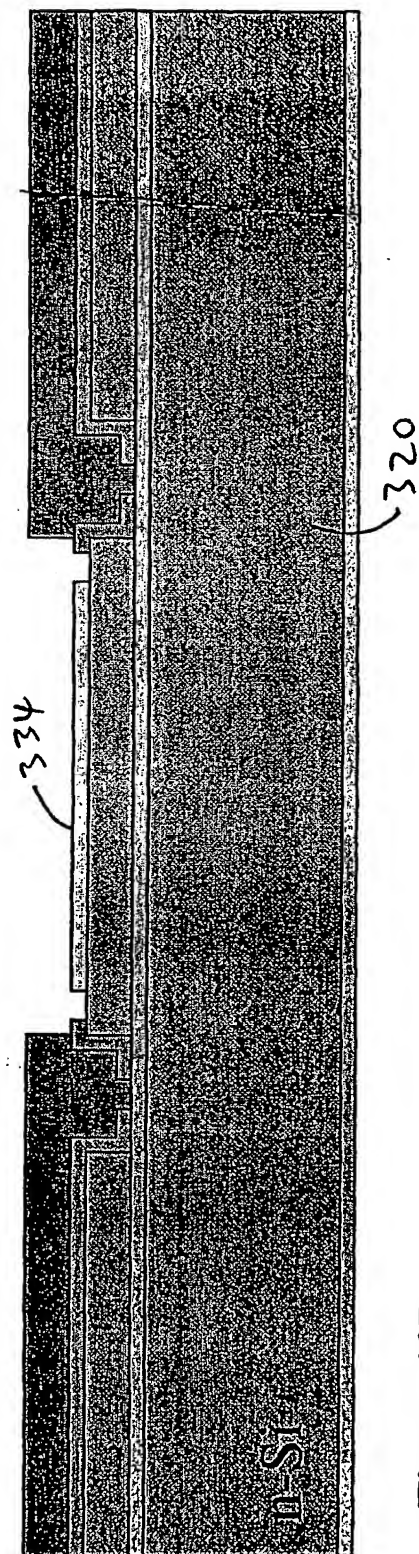


Figure 19I

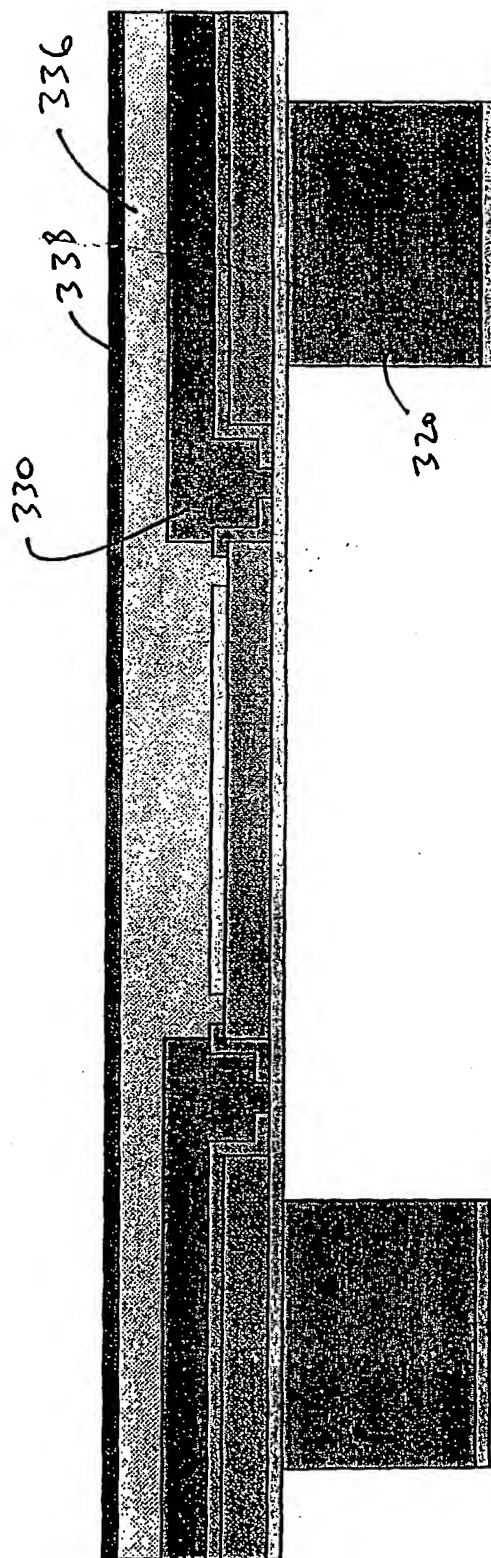


Figure 19J

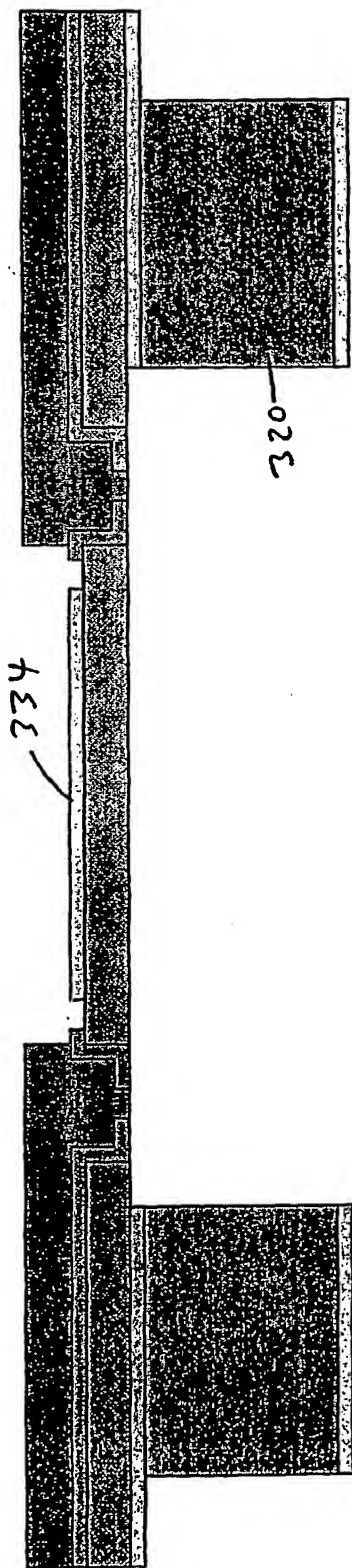


Figure 19K

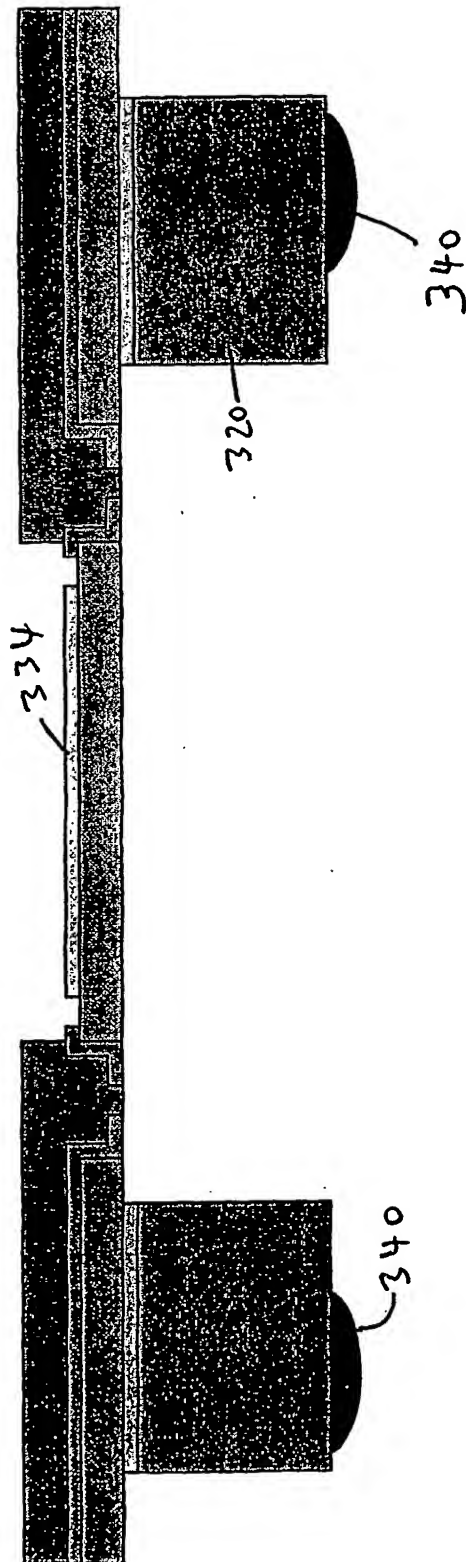


Figure 19L

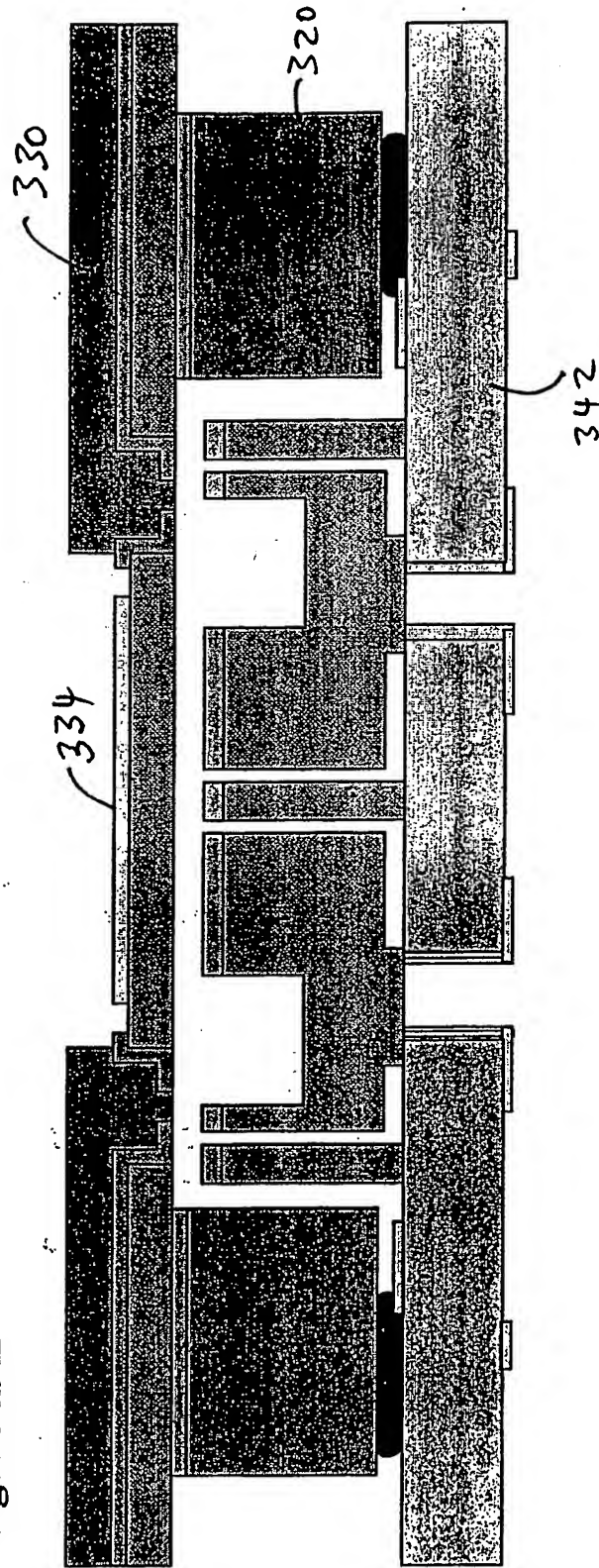


Figure 19M

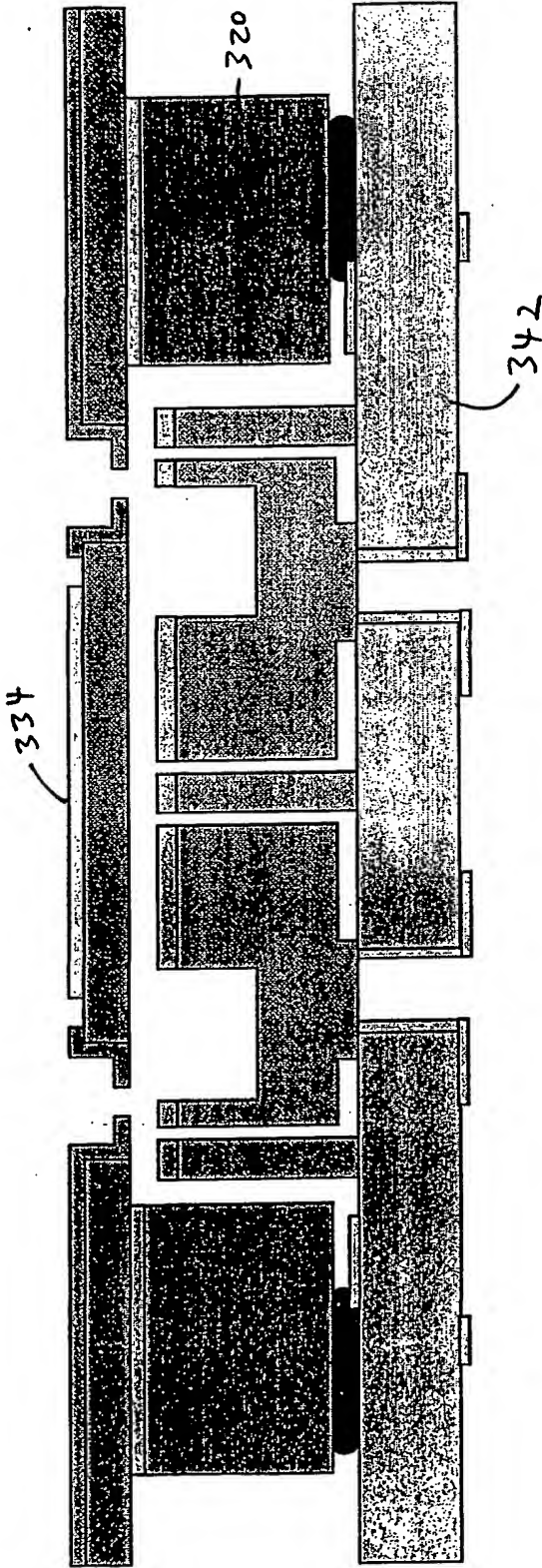
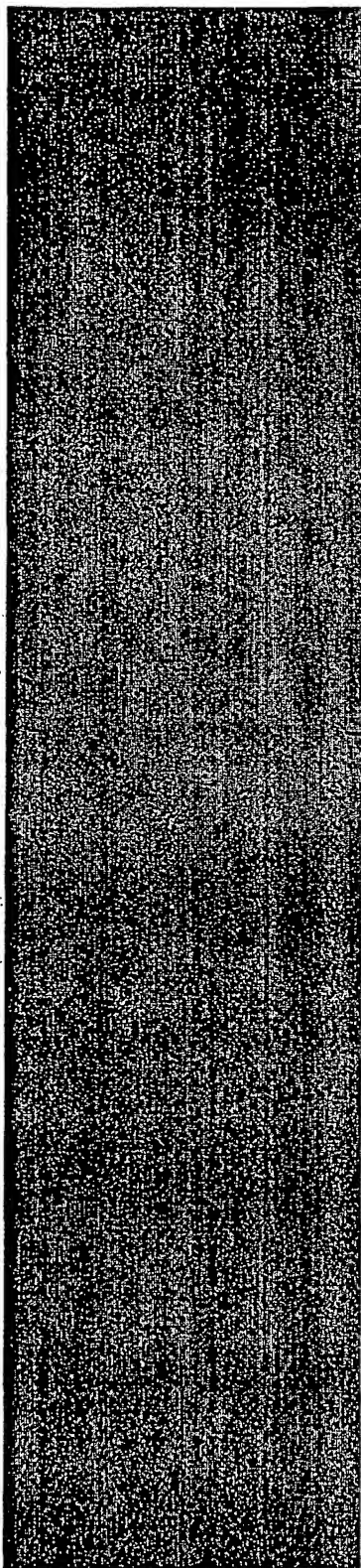
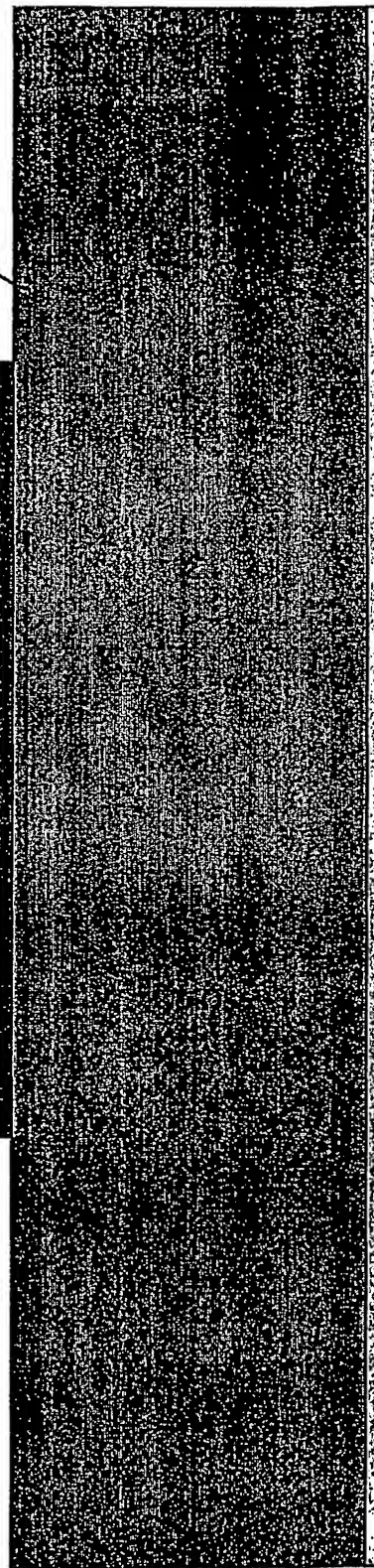


Figure 20A



360

Figure 20B



360

364

362

Figure 20C

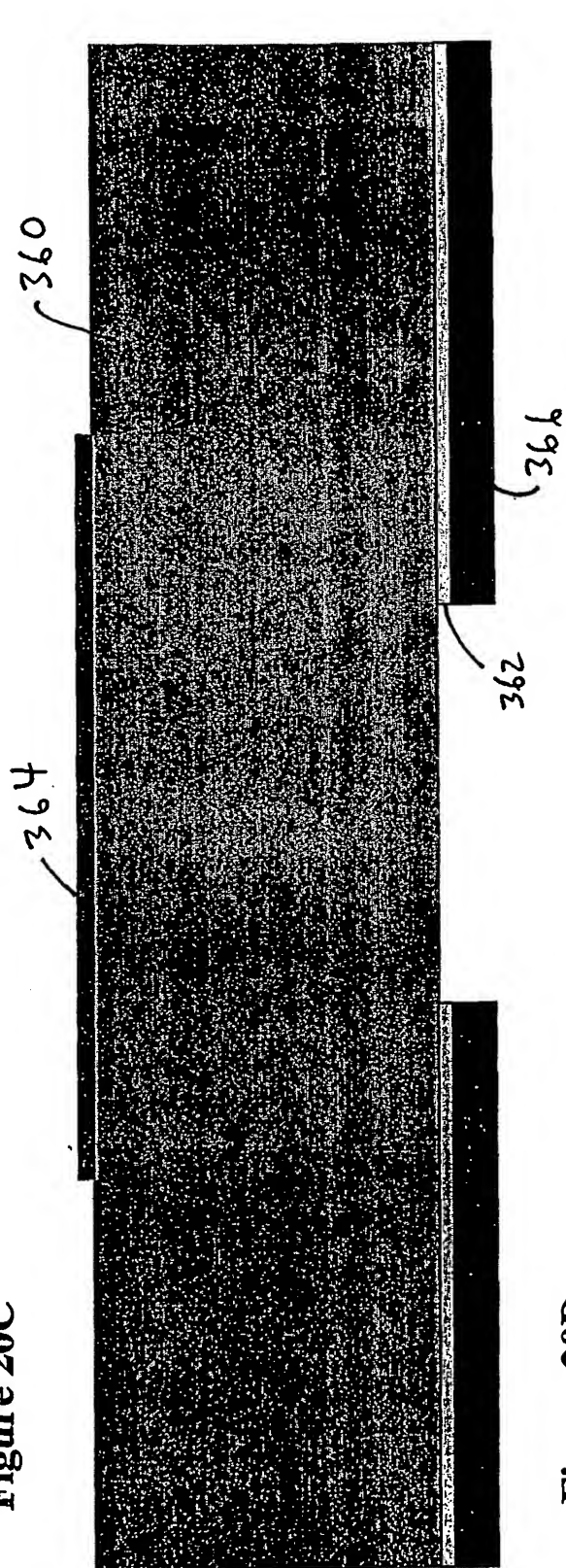


Figure 20D

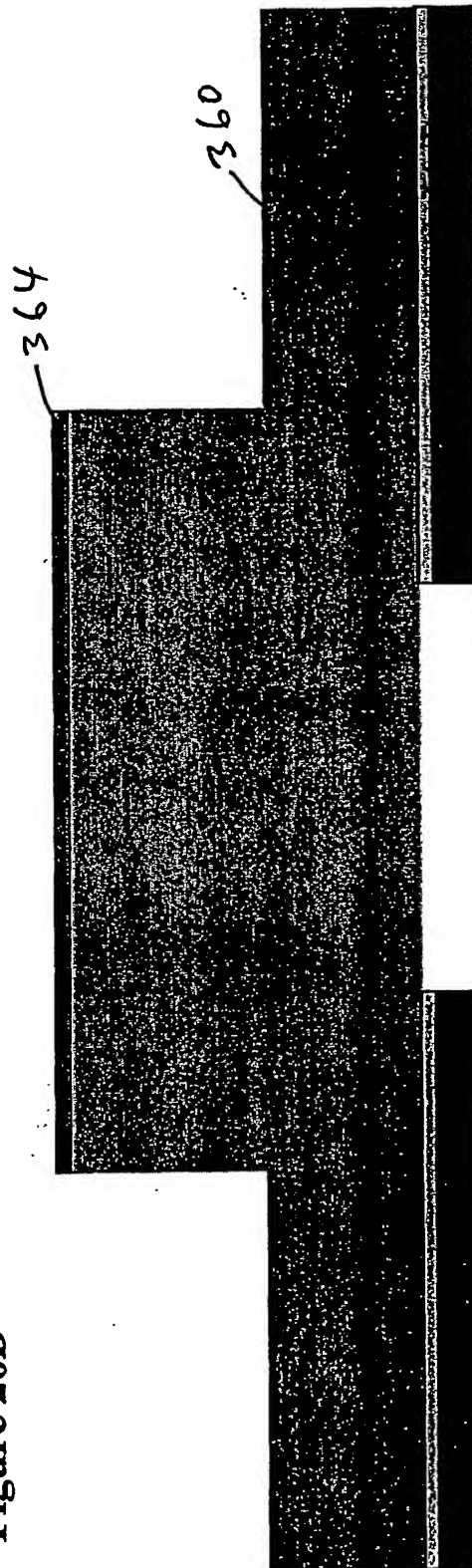


Figure 20E

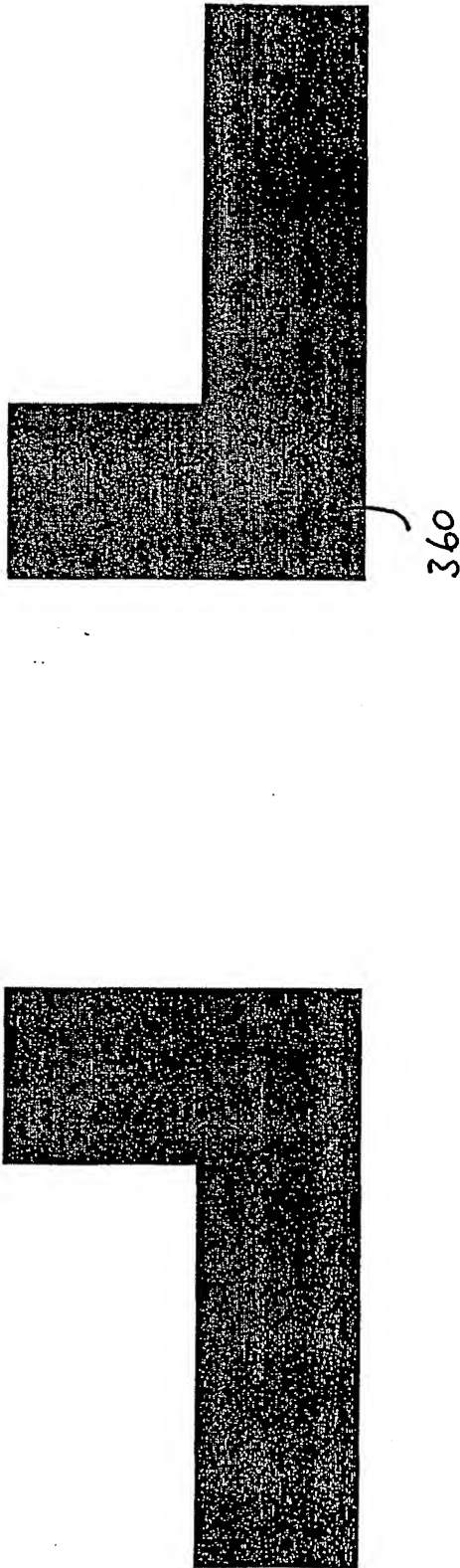


Figure 20F

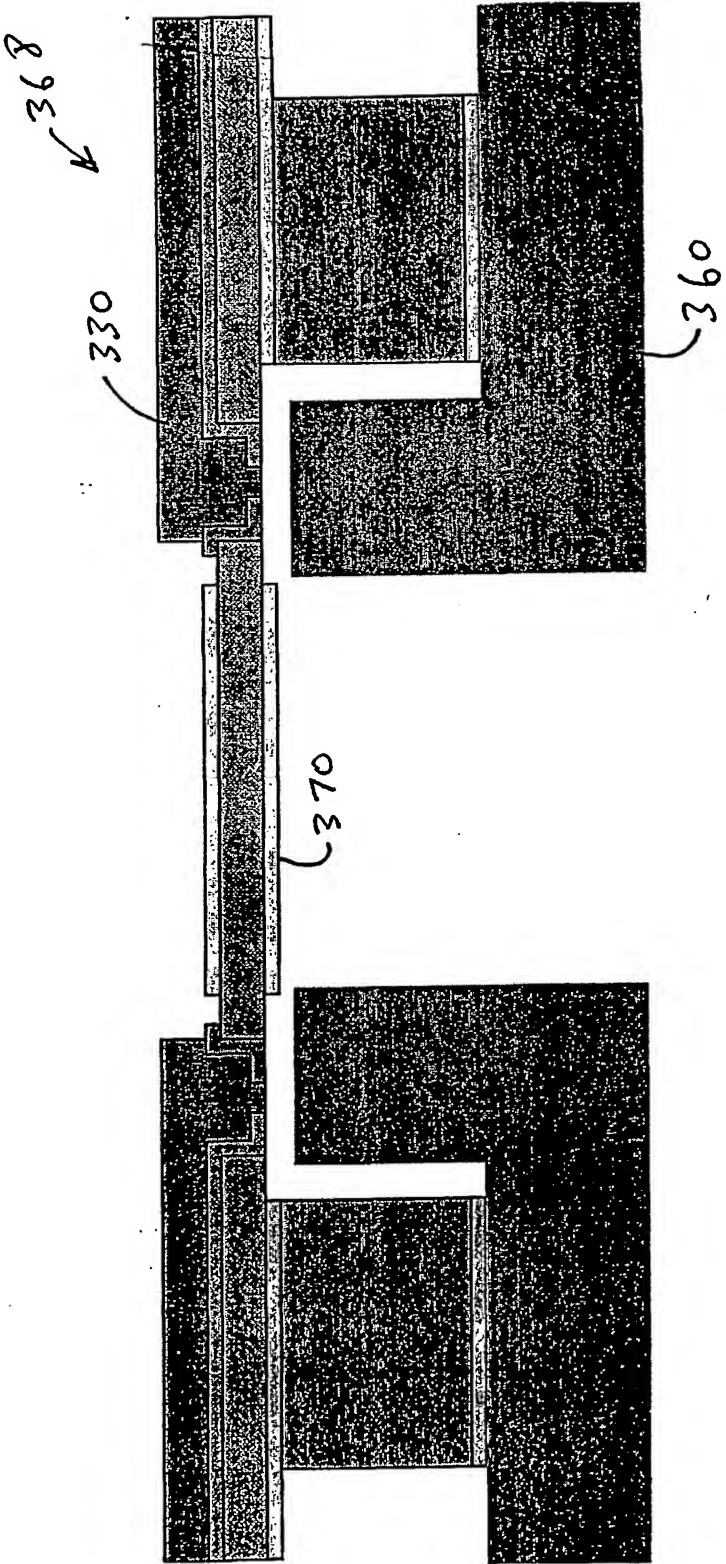


FIG. 21

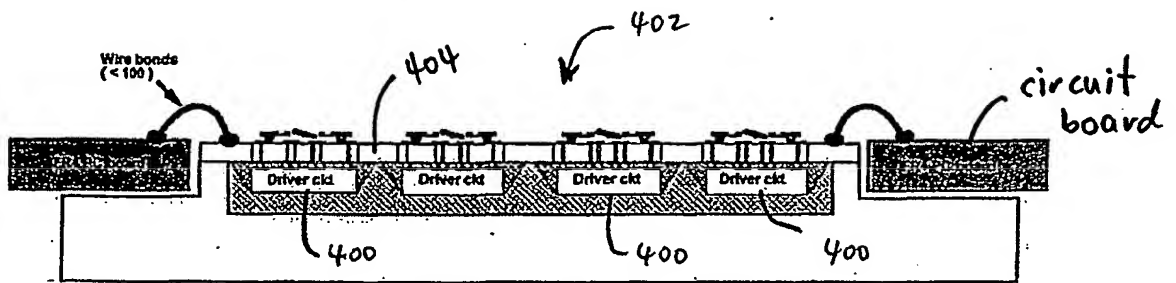
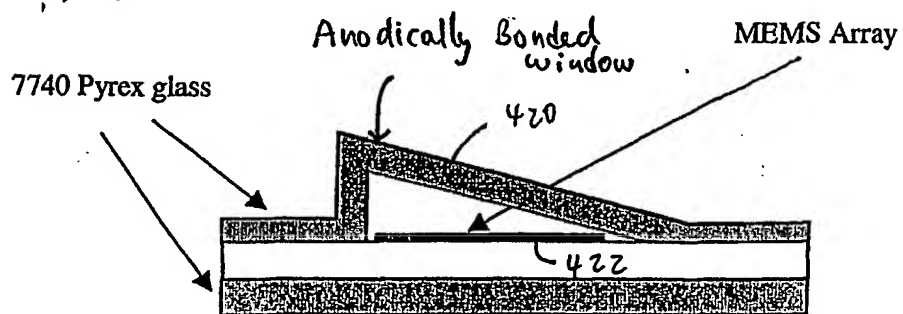


FIG. 22



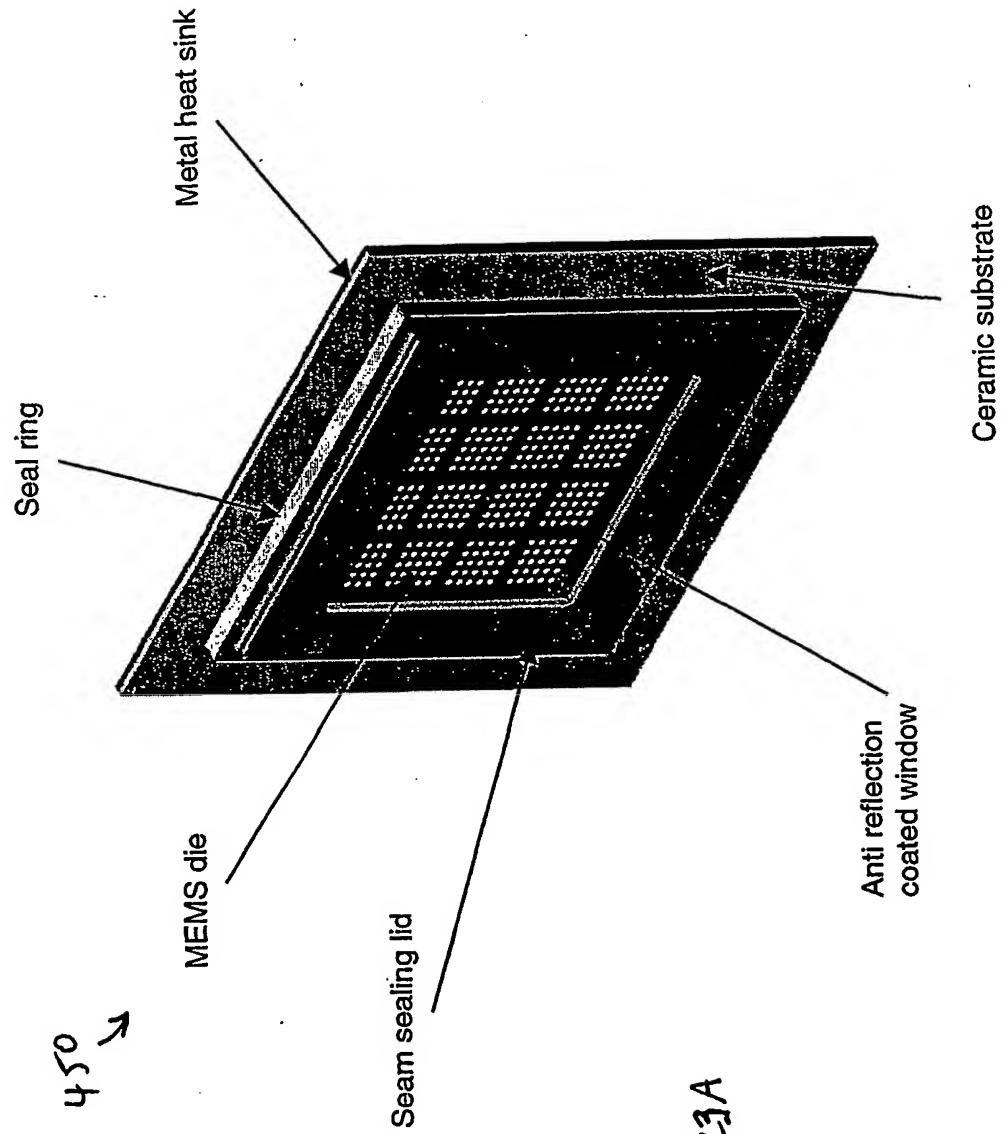


FIG. 23A

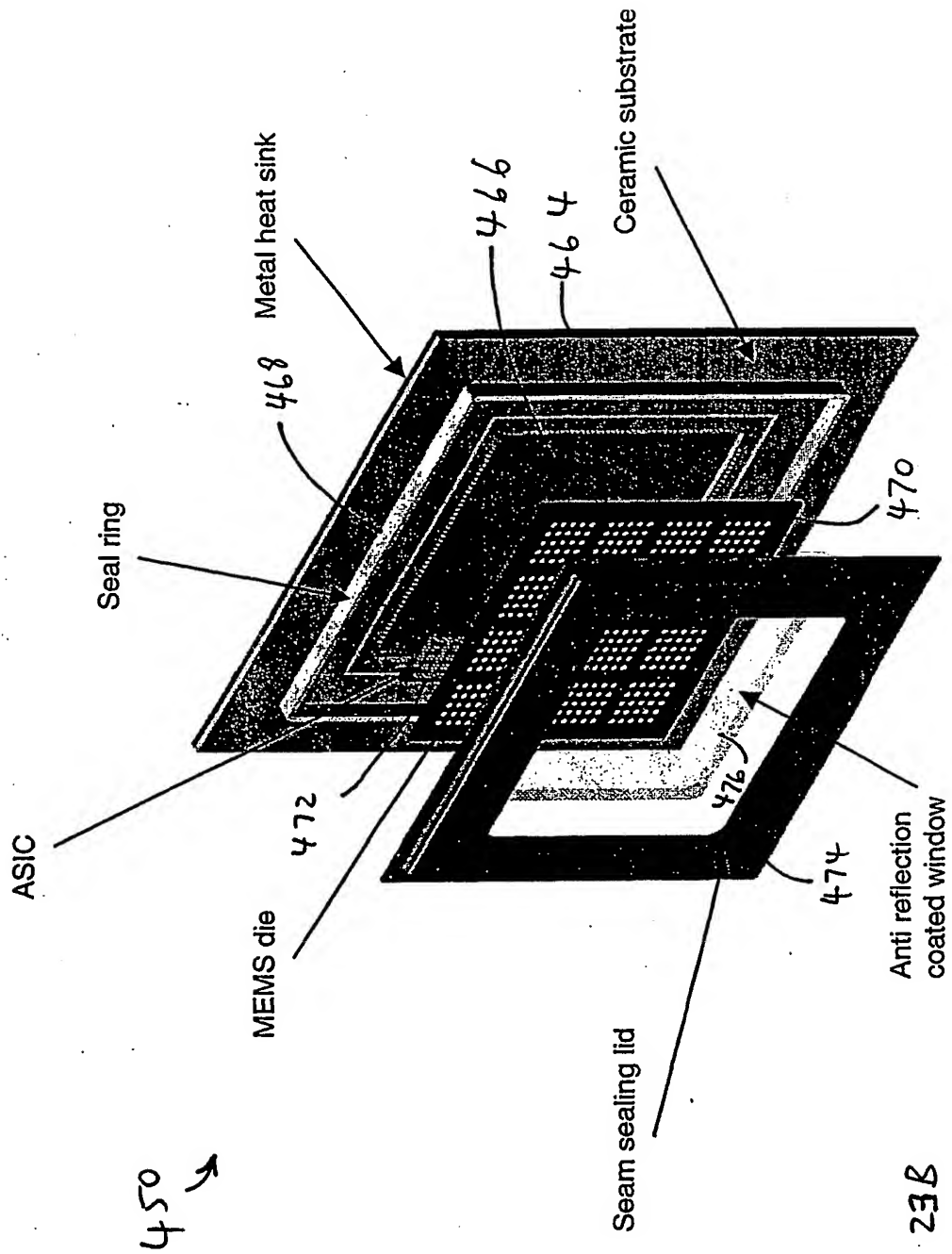


FIG. 23B

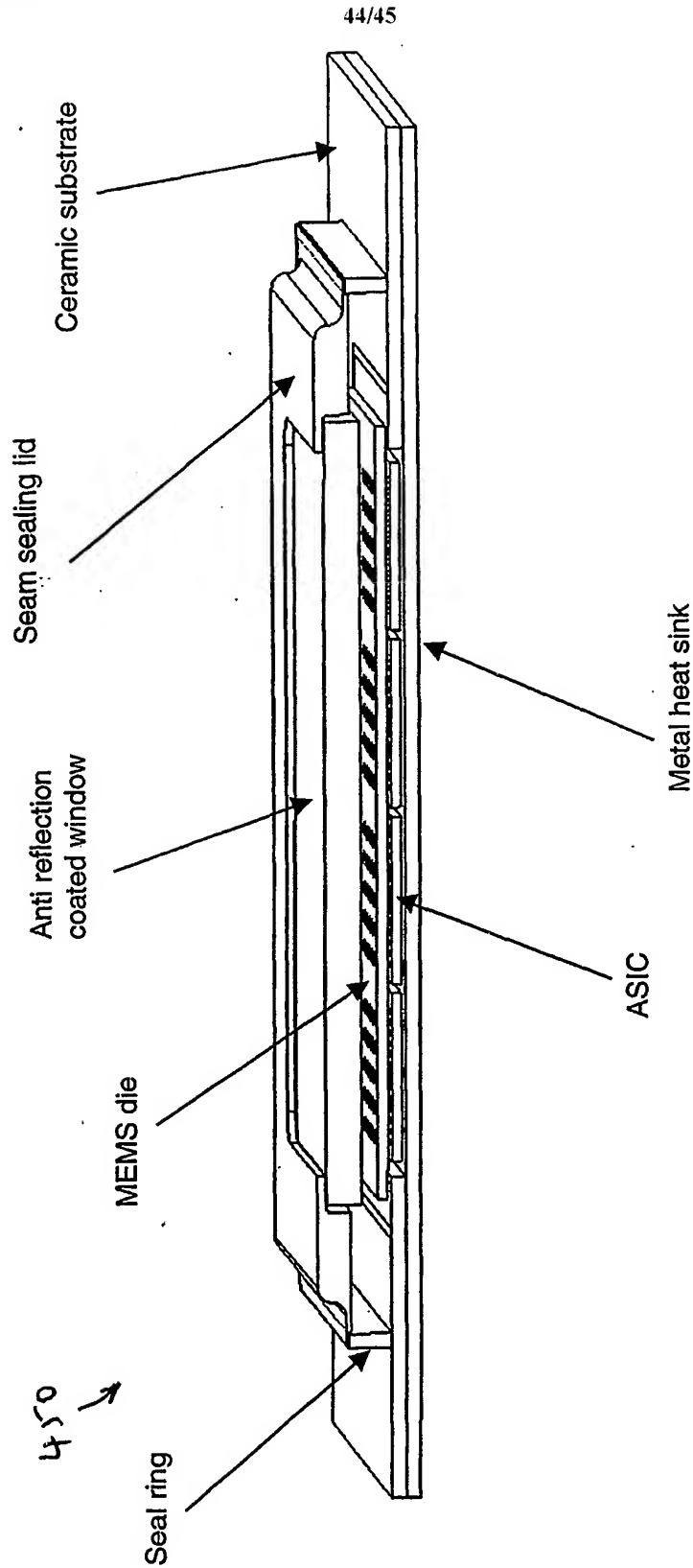


FIG. 23C

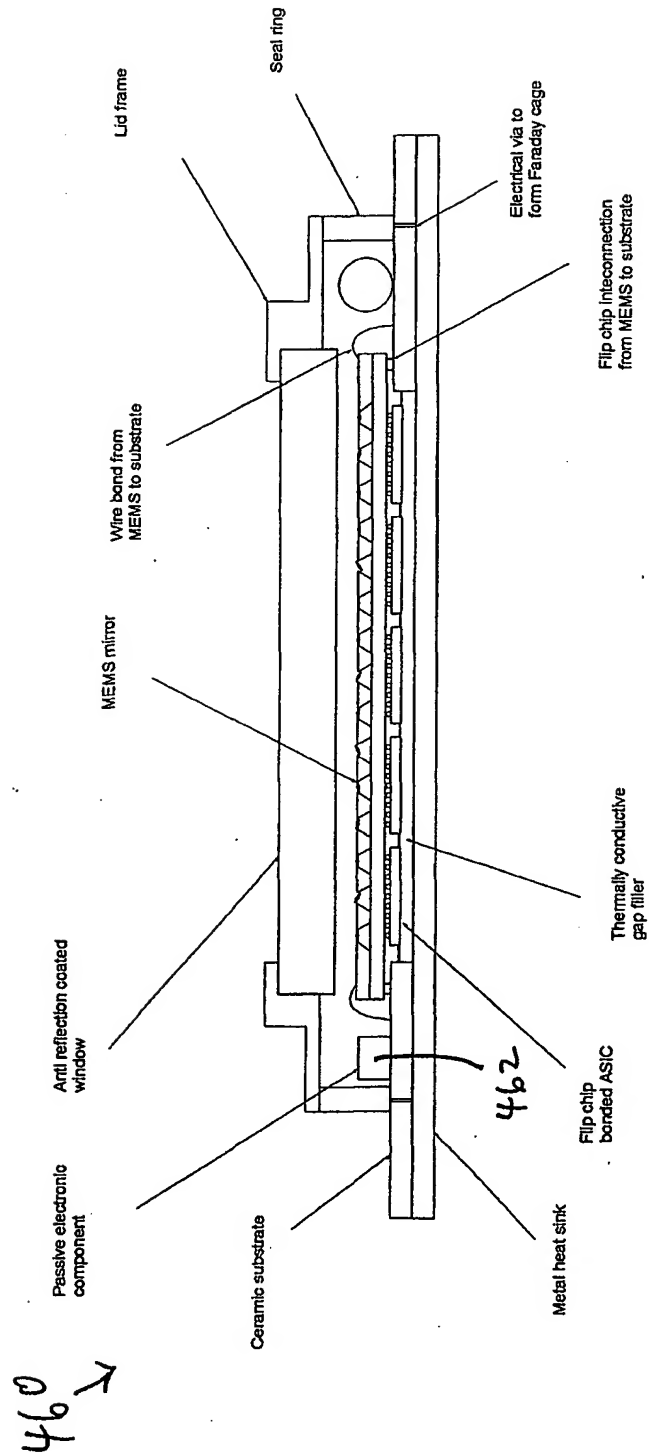


FIG. 24

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US02/07670

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02B 26/08, 5/08

US CL : 359/223-226, 838

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 359/223-226, 838

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NPL

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,912,608 A (ASADA) 15 June 1999 (15.06.1999), Fig. 2.	1-19, 91-101
X	US 5,392,151 A (NELSON) 21 February 1995 (21.02.1995), Fig. 3 and cols. 3-7.	20-39, 79, 107
X	US 5,216,490 A (GREIFF et al) 01 June 1993 (01.06.1993), Figs. 1-14.	40-54
X	US 6,046,840 A (HUIBERS) 04 April 2000 (04.04.2000), Figs. 1, 3A, 3B, 6A, 6B, 13, 14.	55-78, 80-90, 102-106, 108

☐ Further documents are listed in the continuation of Box C.

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Date of the actual completion of the international search

11 July 2002 (11.07.2002)

Date of mailing of the international search report

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